STRATIGRAPHY OF PALEONTOLOGICAL COLLECTING AREAS 106, 107 AND 109, KOOBI FORA REGION, NORTHERN KENYA

by

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STATEMENT OF THESIS APPROVAL

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ABSTRACT

The KBS and the upper Burgi Members of the Koobi Fora Formation are exposed on the eastern shore of Lake Turkana in northern Kenya ~11 km southeast of Koobi Fora in paleontologic collecting areas 106, 107 and 109. The upper Burgi Member is only exposed in very low lying outcrops in the southern portion of the study area therefore a stratigraphic section for this unit was not established. All other strata in the areas listed belong to the KBS Member and total ~145 m of section.

During KBS Member time a large lake was present in this region, and most of the KBS Member in this area was deposited in nearshore lacustrine settings as lake level fluctuated. The most prominent mappable beds in the study area are mollusc-packed sandstones, also called arenaceous bioclastic carbonate beds (ABC), a term that is also applied to algal beds. These beds formed in the nearshore environment of ancient Lake Turkana. They are poorly- to well-cemented and form easily mapped pavements that provide both stratigraphic and structural control.

Four tuffs known from previous studies have been identified within the KBS Member in the study area: the KBS Tuff, the Brown Tuff, the Orange Tuff, and the Asa Tuff. In addition to these named tuffs, another tuff, K09-572, lies about 5 m above the Asa Tuff. The Asa Tuff has not been described elsewhere and is defined here. The KBS Tuff is well dated at 1.869 ± 0.021 Ma, but direct ages have not been measured on any of the other tuffs mentioned. Although this is the case, the Orange Tuff has been correlated

with Tuff J of the Shungura Formation, and also with the Kayle Tuff-1 at Konso in Ethiopia where it lies 2.5 m below the Kayle Tuff-2, which has been dated at 1.735 ± 0.03 Ma. In the Nachukui Formation, west of Lake Turkana, the Asa Tuff lies below the Morutot Tuff, hence its age is between 1.735 and 1.61 Ma. Tuff J is known to lie above the top of the Olduvai Event, for which the current age estimate is 1.778 Ma.

Other workers relate fluctuations in the level of Lake Turkana to Milankovitch cycles which, from studies of sapropels in the Mediterranean Sea, are known to drive the intensity of monsoonal rains over the Ethiopian highlands. These highlands are the headwaters of the Omo River, which feeds Lake Turkana. Thus any change in precipitation affects the level of Lake Turkana. It has been proposed that ABCs only form during dry periods of time in near shore environments.

Milankovitch cycles have been proposed to control the formation of ABCs, because in paleontological collection Areas 102 and 103, which lie north of the study area, available chronological control provided a reasonable fit to the number and approximate age of these units. Additional age control provided by the Orange Tuff suggests that at least in Areas 106, 107, and 109, the number of ABCs present within a local section is location dependent, and cannot obviously be correlated with Milankovitch cycles.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGMENTS

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I would also like to thank Drs. Ronald L. Bruhn and Thure E. Cerling for their guidance as committee members and mentors. Michael Buchanan acted as my field assistant (and me as his) in the field. I cannot imagine what our field season would have been like without his companionship. Also, I am immensely indebted to our three assistants, Simon Ilar (of Warto), Moses Njoroge (of Nairobi), and Mutua Kiko Nying'ole (of Ileret), whose patience and good humor knew no bounds.

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1. INTRODUCTION

The Omo-Turkana Basin has been a hotspot for anthropological and paleontologic studies since the 1960s, producing hundreds of hominid fossils and thousands of vertebrate fossils. Stratigraphy and geochronology have been the backbone of these paleontological studies because they piece together the basin's geological history and provide an understanding of the environment and time in which past life forms existed.

Lake Turkana (Rudolf) occupies a closed basin in northern Kenya within the Omo-Turkana Basin. The principal water source for the lake is the Omo River, which enters from the north, draining the southern part of the Ethiopian highlands. The Turkwel and Kerio Rivers are also important water sources that rise in the highlands of Kenya and eastern Uganda and debouch into the southwestern part of the lake. Pliocene and Pleistocene strata within the basin record varying depositional environments in the area between 4.3 and 0.7 million years ago. Although these deposits are expansive, their outcrops are discontinuous. Contained within these deposits are fossil remains, lithic artifacts and other clues relating to the life that occupied the region through time. Study of these traces of past life and the sediments housing them provides evidence of the biological and geological evolution of this region. This study documents the stratigraphy, structures and paleoenvironments of a ~100 km^2 area along the eastern shore of Lake Turkana (Figure 1).

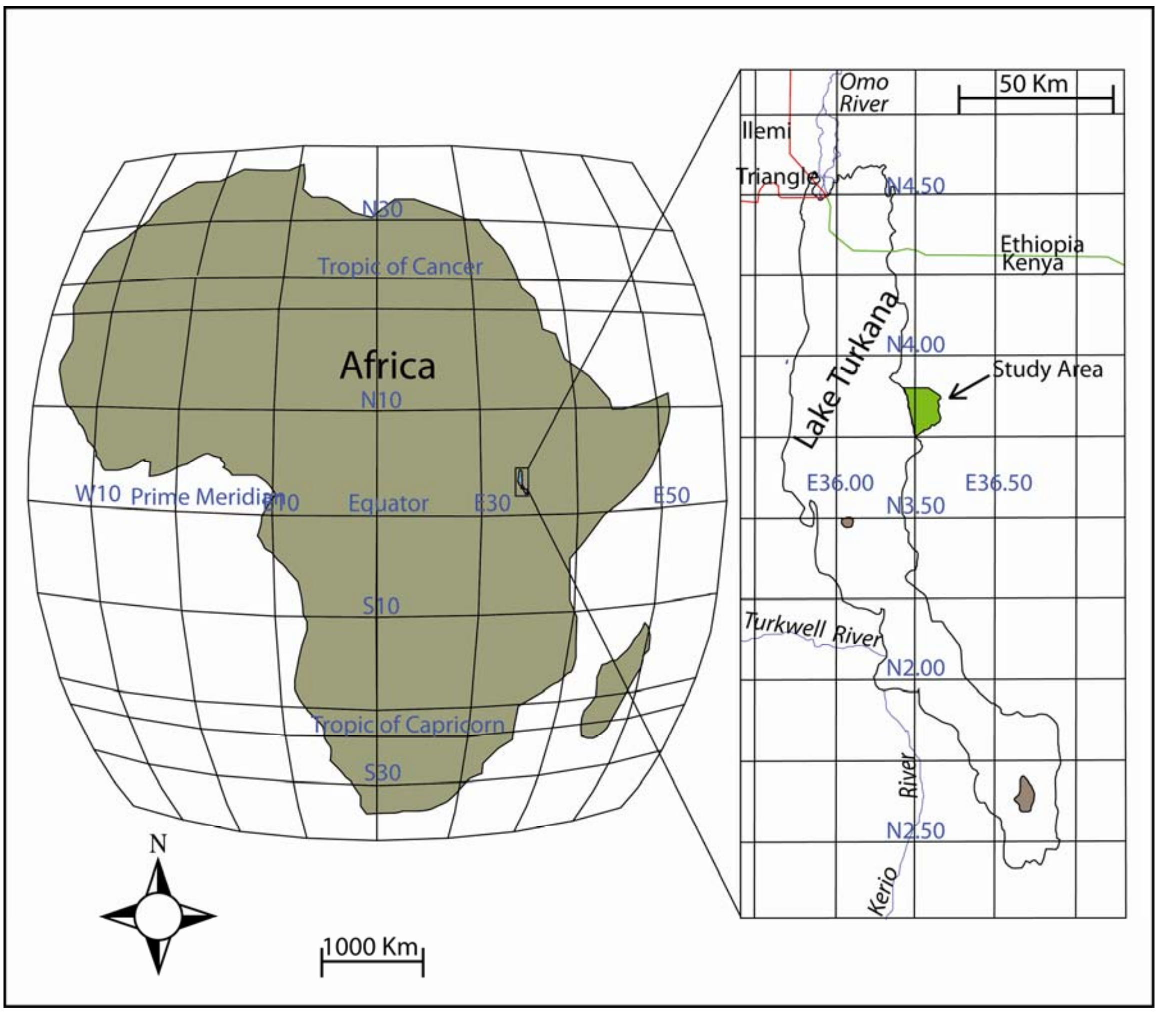


Figure 1. Location of the study area.

1.1 Purpose

The purpose of this study was to map and document the stratigraphy of an area with discontinuous exposures of Pliocene and Pleistocene sediments located along the eastern margin of Lake Turkana. The study area is significant to science because hundreds of early hominids and thousands of ancient vertebrate fossils have been found within the Turkana Basin although to date none have been found in this study area. These fossils provide information concerning past life forms in this region and their evolution over the past four million years (e.g., Cooke, 1972; Cooke and Maglio, 1972; Harris, 1991; etc.). The geology of much of the Koobi Fora region is reasonably well known through the detailed work of Feibel (1981, 1983 and 1988), Feibel et al. (1986, 1991), Tindall (1983, 1985), Burggraf (1976), White (1976), Vondra et al. (1971), Bowen (1974), Bowen and Vondra (1973), Bowen et al. (1972) Findlater (1976 and 1978a, b), Brown (1994), Brown et al. (1982, 1985, 1986, 1991, 1997, 2006, 2008), Cerling (1977), Cerling and Brown (1982), Cerling et al. (1988), Raynolds (1972), Johnson (1973a, b, c) Johnson et al. (1976). Portions of the geology of the Omo River drainage were described by Davidson (1973). Walsh and Dodson (1969) provided a reconnaissance map of North Turkana west of the lake. Wilkinson (1988) completed a regional geological sheet that covers the study area. Areas 100, 101, 102, 103, and 104 situated north of the study area have been investigated by Bowen (1974), Johnson (1973) and Feibel (1983, 1988).

This thesis pieces together the detailed geology of an area ~100 km^2 in extent and provides a deeper understanding of the basin as a whole. Key aspects of this study include improving stratigraphic control, interpreting paleoenvironments, defining marker beds and placing the strata into a chronological framework through tephrostratigraphy.

1.2 Geography of the Study Area

The region east of Lake Turkana throughout which Pliocene and Pleistocene strata crop out was divided into a system of paleontologic collection areas by early workers (Figure 2). In general, boundaries of these areas were placed along prominent ephemeral drainages, faults, or outcrop limits. These areas were numbered so that areas 1–99 lie in the Ileret Region, 100–199 in the Koobi Fora Region, and 200–299 in the Allia Bay Region. The field area for this study is located in Paleontological Collection Areas 106, 107 and 109 (Figure 2), hereinafter referred to as Area 106, Area 107, etc.

The study area is located approximately 11 km southeast of Koobi Fora Camp. Elevations range between 360 m (lake level) and ~480 m. The area is extremely arid with an average of 172 days/year above 35ºC as recorded by the Bethany House in Lodwar, located about 45 km west of the western shore of Lake Turkana. Due to the high temperatures and low precipitation (<259 mm/year) the area supports a variety of C_3 shrubs and C_4 grasses that have adapted to the extreme conditions (Figure 3). Geographic names are based on local Dhaasanac names obtained from a field assistant, Mutua Kiko Nying'ole, who is intimately familiar with the area.

1.3 Previous Work

Geologic study began in the Koobi Fora and Ileret Regions in 1968 after Richard Leakey visited the northern part of the region in 1967 on a helicopter trip from the Omo Valley where he led the Kenyan contingent of the International Omo Research Expedition. On that trip he noted archeological and faunal remains, on which

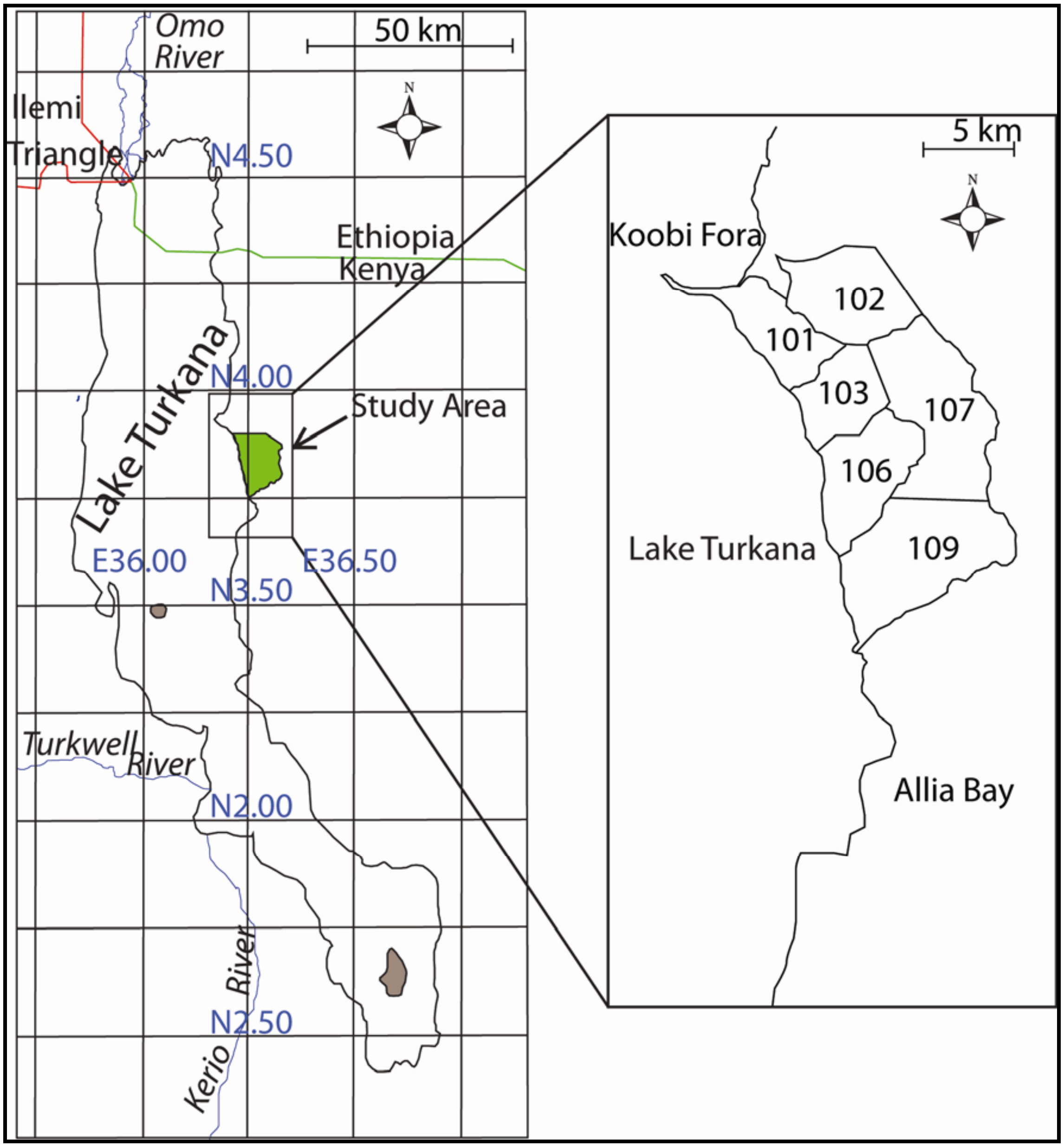
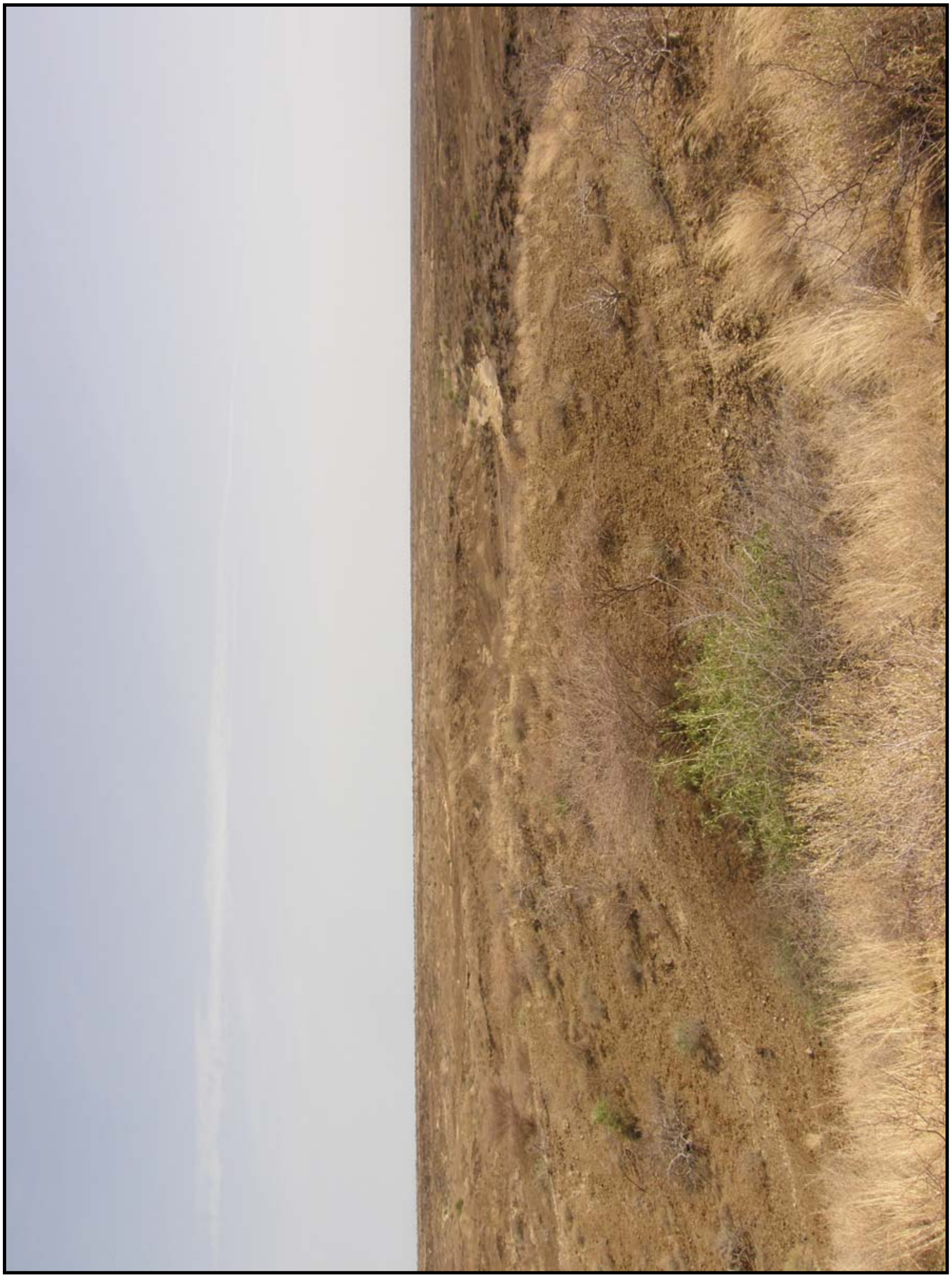


Figure 2. Map of paleontologic collection areas applicable to this study (adapted from Brown and Feibel, 1986). Collection Areas 106, 107 and 109 are studied in this research.

Figure 3. Photograph of part of the study area that exemplifies the aridity of the climate and shows examples of C3 shrubs (*Commiphora* sp., *Acacia reficiens*, *Sericocomopsis pallida*, and *Salvadora persica* (green) visible, and C4 grasses, here largely *Aristida* sp., and *Leersia* sp.). This photograph was taken looking south-southwest at 3.8636 N, 36.2574 E.



basis he mounted an expedition to the region the following year—1968. Many geologic studies have been performed in the region since then. Even though a great deal of work has been performed, much of the region's geology is still only known on a reconnaissance level. Bowen (1974) produced the first map of the entire region as part of his doctoral dissertation, and Findlater (1976) completed additional mapping at a somewhat more refined level. Much of the previous work concentrated on the Karari Ridge located about 30 km northeast of Koobi Fora because many hominid fossils and lithic artifacts were found there (e.g., Isaac, 1973). Early, error-laden work on the geochronology was performed by Frank Fitch (Birkbeck College, London) and John Miller (Cambridge University) and colleagues (e.g., Fitch and Miller, 1976), but since 1976 essentially all potassium-argon and $^{40}Ar/^{39}Ar$ work has been carried out by Ian McDougall at The Australian National University, Canberra. Recent reviews are given by McDougall and Brown (2006) and McDougall and Brown (2008).

Little detailed geological work has been done in the study area beyond that by Bowen and Findlater described above, but Craig Feibel (Rutgers University) mapped a small part of the northern extent of Area 106 during the 1980s. Feibel's M.S. thesis (1983) and part of his PhD dissertation (1988) deal with the stratigraphy of Areas 102 and 103 to the north and northwest of the study area.

2. METHODOLOGY

2.1 Field Work

Fieldwork was performed during June and July, 2008. During the first ten days of study F. H. Brown assisted the author by giving a general introduction to the geology of the Koobi Fora Region and instruction concerning what field work needed to be performed. The remaining weeks in the field were spent with a local assistant, Mutua Kiko Nying'ole and Michael J. Buchanan, a fellow graduate student from the University of Utah. Field work was carried out from a base camp at Koobi Fora.

2.2. Geologic Mapping

Google Earth imagery in conjunction with aerial photos was used as base imagery for geologic mapping. Laterally continuous mollusc-packed sandstones, tuffs and algal beds were chosen as marker beds in the region and mapped using standard techniques (Compton, 1962). The extent of each bed was followed and marked on a base image. A handheld global positioning system (GPS) instrument was used to check location accuracy. All latitudes and longitudes are referenced to WGS84 datum and are expressed here in decimal degrees.

2.3. Stratigraphic Measurement

The stratigraphy was defined within the field area using standard techniques described by Compton (1962). In areas where section was poorly exposed, a hoe was used to scrape a clean outcrop surface. A Brunton compass was used to measure the strike and dip of beds. Stratigraphic sections were measured with a Jacob's staff and the inclinometer on a Brunton Compass. Lithologic descriptions of individual beds were made through examination of fresh outcrop and hand samples with the aid of a 10X hand lens.

2.4 Laboratory Analysis

Laboratory work was performed at the University of Utah's College of Mines and Earth Sciences following field work. Laboratory work dealt primarily with the separation and analysis of volcanic glasses from tuffs and tuffaceous sediments collected in the field.

Separation began with crushing the samples using a mullite mortar and pestle. The crushed samples were then sieved and the -120+170 (90–125 micron) and -60+120 (125–250 micron) grains were kept for analysis. These fractions were then washed with water, 5% nitric acid and 5% hydrofluoric acid removing carbonate and clay from the samples. Volcanic glass was then separated from other minerals using a Frantz™ magnetic separator.

After separation the samples were mounted in a methyl methacrylate polymer disc. Nine samples and a single standard (obsidian MM-3 from the Mineral Mountains, Utah) were mounted in each plug using a two part epoxy to set them after which they were polished and carbon coated.

Once the samples were carbon coated at least 10 points from each sample were analyzed using a Cameca SX-50 ™ electron microprobe. This microprobe has four wavelength-dispersive spectrometers and was set to an electron voltage of 15 kV, a beam current of 25 nA and a beam diameter of 5–25 microns. The natural obsidian standard was used for O, Si, Al and K calibration and remaining elements were standardized using synthetic oxides and minerals. The concentration of each element was calculated using the relative peak intensities and the $\Phi(\rho Z)$ algorithm of Pouchou and Pichoir (1991). A more detailed account of the analytical methods used is provided by Nash (1992).

2.5 Statistical Analysis

After analysis of each sample was completed, the abundance of each element measured was converted to weight percent oxide. Unary results (single outlying shard compositions) and results with high/low totals (<98% and >102%) were removed from the dataset; the remaining results for each sample were then divided into compositional modes. The chemical composition of each mode was then averaged for each analyzed sample. The resulting analyses were then compared to average chemical composition of other tuffs from the Turkana Basin using F.H. Brown's master data set.

Comparison to the master data set was done using several techniques. First, the average chemical composition of each sample was sorted within the master data set relative to single elemental concentration such as Fe_2O_3 or Al_2O_3 removing samples whose composition lay outside the range of the sample in question. After this had been done for several elements, bivariate plots were created of elements against each other such as Al_2O_3 vs. CaO or Fe_2O_3 vs. CaO. These plots were used to divide the remaining samples into individual modes. This process not only separated the samples into their individual modes but also resulted in determining if a mode was the same composition as a mode in a previously analyzed tuff.

3. TECTONIC SETTING

3.1 East African Rift System

The Turkana Basin is located in northwestern Kenya and is the result of tectonic stresses within the East African Rift System (EARS) (Figure 4).

The EARS begins at the Afar triple junction in northern Ethiopia where it meets the Red Sea and the Gulf of Aden, and then stretches southward into Kenya and Tanzania. The EARS is composed of several rift systems. Most of the older rift elements have been overprinted by more recent Tertiary rift systems and are only present in erosional Permo-Triassic to Jurassic Karoo troughs (Rosendahl, 1987).

The EARS extends thousands of kilometers and is a world class example of a modern active continental rift. The morphology of the EARS is very similar to that found along many oceanic ridge systems, where basins are created between overlapping ridge segments. The EARS is a topographic high that is volcanically active. Rift valleys within the East African Rift System comprise a series of asymmetric half graben basins that are on the order of 100 km in length. In many cases these basins are occupied by large lakes such as Lake Turkana and Lake Tanganyika (Keller, 2002).

The EARS can be broken into three primary sectors: the Afar triple junction, the Eastern Branch (Gregory and Ethiopian Rifts) and the Western Branch. The Eastern

Figure 4. Principal structural elements of the East African Rift System.

Branch and the Western Branch overlap each other in a 300 km wide extensional basin system (Ebinger and Yemane, 2000).

The Turkana Basin occupies a closed drainage within the eastern branch of the EARS. The eastern branch of the EARS is composed of two primary rifts, the Gregory rift centralized in Kenya and the Ethiopian rift to the north. The Turkana Basin is located within the Gregory rift in a depression between the Kenya and Ethiopian domal uplifts.

The Turkana Basin is topographically low in comparison to other sections of the EARS, although Lake Magadi lies at comparable elevation. The basin is situated in what has been termed the broadly rifted zone, which is the widest known portion of the EARS (300 km), besides the Afar Triangle (Ebinger, 2000). The Broadly Rifted zone is composed of a sequence of half grabens and is formed by the overlap of the Ethiopian Rift and the Gregory Rift. In the widest location, the rift is formed by 3-4 large half grabens, each of which is down-faulted towards the east so that this part of the region is completely atypical of the EARS, and in some ways is more reminiscent of the structure of the Basin and Range (Ebinger and Yemane, 2000). Crustal thinning due to this rifting may have produced crust as thin as ~20 km and lithosphere with an elastic thickness of 3.5 km under the Turkana Basin, which is thought to be the thinnest crust in the EARS (Hendrie et al., 1994).

3.2 Faulting in the Study Area

A fault system in the field area consists of 6 faults that link to one another in different locations. These faults generally trend northeast to southwest or north to south. Examination of these faults in the field and their relationship to tuffs and other stratigraphic marker beds show that the offsets produced on a single fault in this area most likely average 15 m or less. Often the only trace of a fault in the field is a slight buckle in a mollusc-packed sandstone pavement or the abrupt end of one of these pavements. After connecting known faults to each other it becomes clear that offsets on this fault system decrease in northern parts of the field area and increase southward. Due to the minimal offsets noted, faulting was not been taken into account when comparing stratigraphic columns produced by this study but has been taken into account when placing age definitions on sediments noted on the geologic map produced by this study.

4. GEOLOGIC SETTING

The geology of the Turkana basin is composed of four primary components: early Paleozoic crystalline basement (gneiss and schist), Cretaceous sandstones, Eocene to Miocene volcanic rocks with intercalated sedimentary strata, and Pliocene to Pleistocene sedimentary rocks. Basement rocks are exposed to the north and northeast of the basin, on Labur (northwest of the lake), over much of the Turkwel drainage, and southeast of the lake where exposures are virtually continuous from south of Mt. Kulal to about 40 km south of Baragoi along the eastern flank of the rift valley. The source of much of the coarser clastic detritus in the basin is derived from such rocks, which is apparent from the abundance of quartz and pink perthitic feldspars in sandstones. Most of the Tertiary volcanic rocks are basaltic, but rhyolitic ash flows, lavas and phonolites are also present. These are found throughout the region both in situ and within gravels that cover exposures of the Koobi Fora Formation. In the region around Koobi Fora, there are also several volcanic plugs and ignimbrite sheets. Watkins (1986) gives a summary of regional volcanism in the area, and other accounts are provided by Williams (1969, 1978).

Most sedimentary deposits were laid down in fluvial and lacustrine environments (Vondra and Bowen, 1976, 1978; Findlater, 1976; Feibel, 1983; etc.). Extension has created an asymmetric basin that is occupied by modern Lake Turkana. A lake formed in the Turkana Basin ~2.0 Ma and it has been the site of lacustrine sedimentation ever since.

Through time lake level has fluctuated drastically. Sediments dating between 2.0 and 1.4 Ma record these lake level changes and are well exposed along Koobi Fora Ridge (Figure 5).

Today, Lake Turkana occupies a closed basin and is fed primarily by the Omo River which provides ~80% of the total influx of water. The other ~20% comes from the Kerio and Turkwel rivers, and also from rainfall directly over the lake and onto marginal areas drained by ephemeral streams. At the lake's greatest areal extent it exceeded 25,000 km^2 compared to today's area of 6400 km^2 (e.g., Brown and Fuller, 2008; Butzer et al, 1972). These drastic fluctuations over time have left their trace through the deposition of beach, nearshore, offshore and alluvial deposits. These four rock types are prominent lithologies present within the Pliocene and Pleistocene strata.

Lake level fluctuations may have resulted from several factors including tectonic thinning and stretching of the crust and climatic fluctuations. Lepre et al. (2007) report that vertical shifts between facies on the lake margin are the result of Milankovitch cycles driving the amount of monsoonal rain inputs to the region's drainage basin.

Between 1.9 Ma and 1.87, Ma deltaic sequences dominated sedimentation along the lake margin (Bowen, 1974; Feibel, 1983; Lepre et al., 2007). Between 1.9 Ma and 1.5 Ma, lake levels varied greatly.

About 1.9 Ma, Lake Turkana's areal extent decreased for reasons still unknown. Hypotheses include a drainage break to the northwest into the Nile or to the southeast into the Indian Ocean. Arambourg (1943) states that Lake Turkana must have had a connection to the Nile River based on the presence of molluscs native to the Nile River which suggests that the basin at times has drained to the northwest into the Nile River.

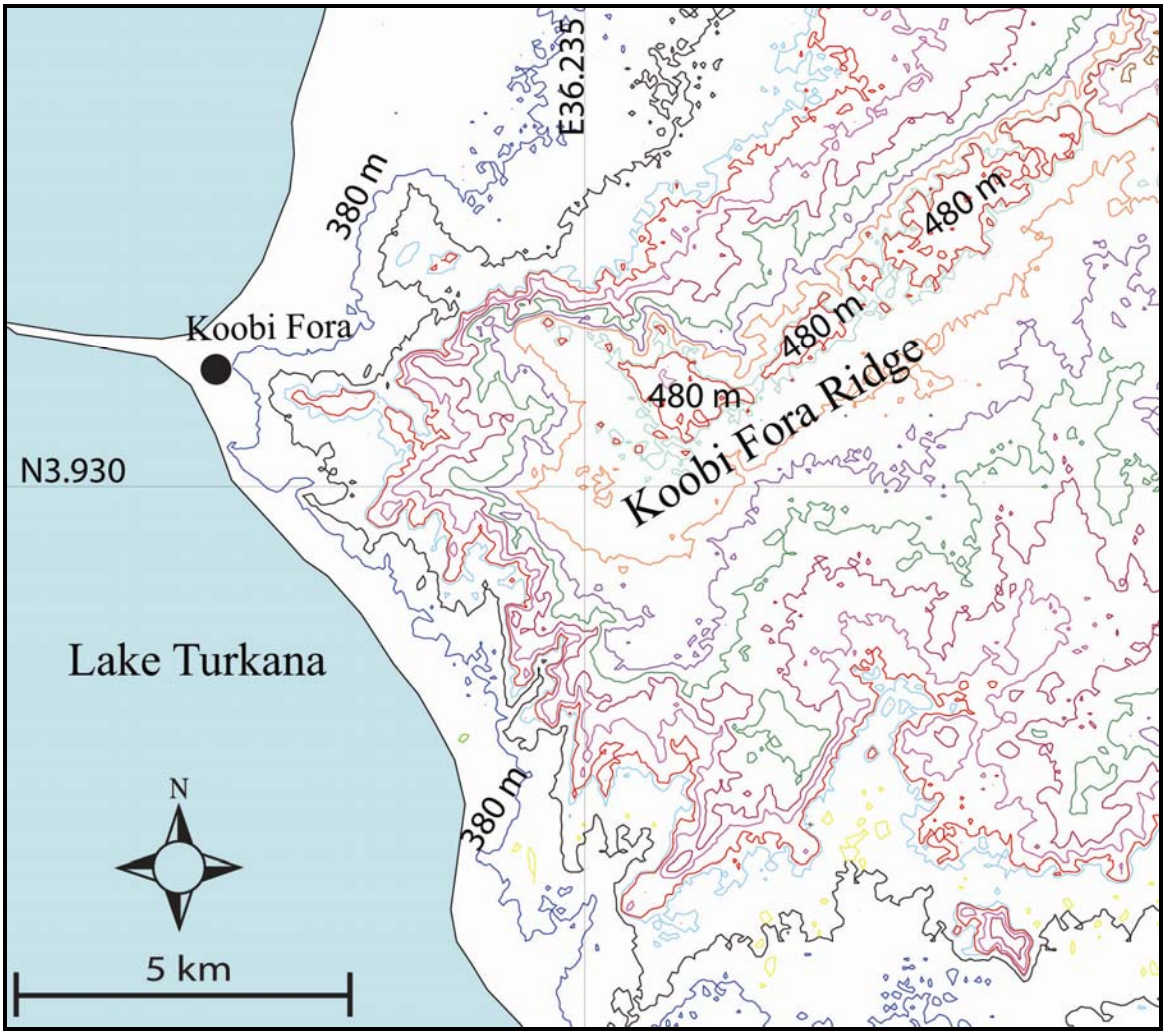


Figure 5. Location of Koobi Fora Ridge relative to Lake Turkana and Koobi Fora. Current lake level is 360 m. The contour interval represented here is 10 m with the lowest prominent contour being 380 m and the highest prominent contour being 480 m.

Feibel (1988) states that the Turkana basin drained to the southeast into the Indian Ocean 1.9 Ma ago during which time the stingray *Dasyatis africana* entered the basin. After 1.5 Ma, the lake filled with sediment and became a fluvial dominated system, for which there is a more or less continuous record of sedimentation for the next 100,000 years.

Four primary facies are represented in the geologic record along Koobi Fora Ridge: alluvial, beach, nearshore and offshore. Alluvial facies are represented by trough cross bedded to planar bedded medium-grained sandstones that fine upward to clayey/silty muds indicative of channels and floodplains (Brown and Feibel, 1991). Beach deposits are poorly sorted, medium- to coarse-grained sands, exhibiting steeply dipping planar crossbedding with occasional ripple marks, shell hash and soft sediment deformation (Renaut and Owen 1991; Blair, 1999). Nearshore deposits are representative of shallow lake waters in a littoral setting with low clastic input. The sediments are poorly sorted, medium-grained, bioclastic sands that contain a variety of molluscs and cryptalgal biolithites (Williamson, 1982; Casanova, 1986; Renaut and Owen, 1991). The offshore facies formed in deep open lake waters with a high clastic input due to the fall out of sediment from suspension. Offshore sediments are generally well sorted, medium- to fine-grained, calcareous mudstones (Bowen, 1974; Brown and Feibel, 1991).

Mollusc-packed sandstones represent the nearshore facies of the Koobi Fora Formation and are very important marker beds that can be followed for considerable distances giving structural and stratigraphic control. In many cases these mollusc-packed sandstones can be stratigraphically related to volcanic ash beds of known age providing insight into the times when deposition occurred in a particular sequence.

5. STRATIGRAPHY

5.1 Nomenclature

The nomenclature for Pliocene and Pleistocene stratigraphy in the Koobi Fora region was formalized by Bowen and Vondra (1973) of Iowa State University. Bowen and Vondra (1973) correlated deposits along the eastern margins of Koobi Fora Ridge and Kubi Algi using “three prominent grey tuff horizons.” The lowest of these tuffs was named the Suregei Tuff complex which they claimed “can be traced around the Kokoi along the western flank of the Suregei cuesta.” This claim, however, is incorrect because the Suregei is not continuous and is not present near the Kokoi. They also state that the Suregei Tuff Complex “extends from immediately east of the Ileret region to about 15 km to the south along the Suregei.” Based on this relationship, they correlated strata in the eastern Ileret area to strata in the Allia Bay area. The middle tuff in the sequence was named the Tulu Bor Tuff, and the upper tuff was correlated with the KBS Tuff. Bowen and Vondra went on to use this tuff sequence but not the tuffs themselves to define the Kubi Algi, Koobi Fora and the Guomde Formations. They proposed that the “Upper Unit” be termed the Ileret Member in the Ileret region because they could not correlate this “Upper Unit” with the deposits in the Koobi Fora and Allia Bay areas.

Brown and Feibel (1986) revised the nomenclature with a new stratigraphic scheme for Pliocene and Pleistocene strata in the Koobi Fora region. This new scheme, made possible by the work of a team from the University of Utah (e.g., Brown and

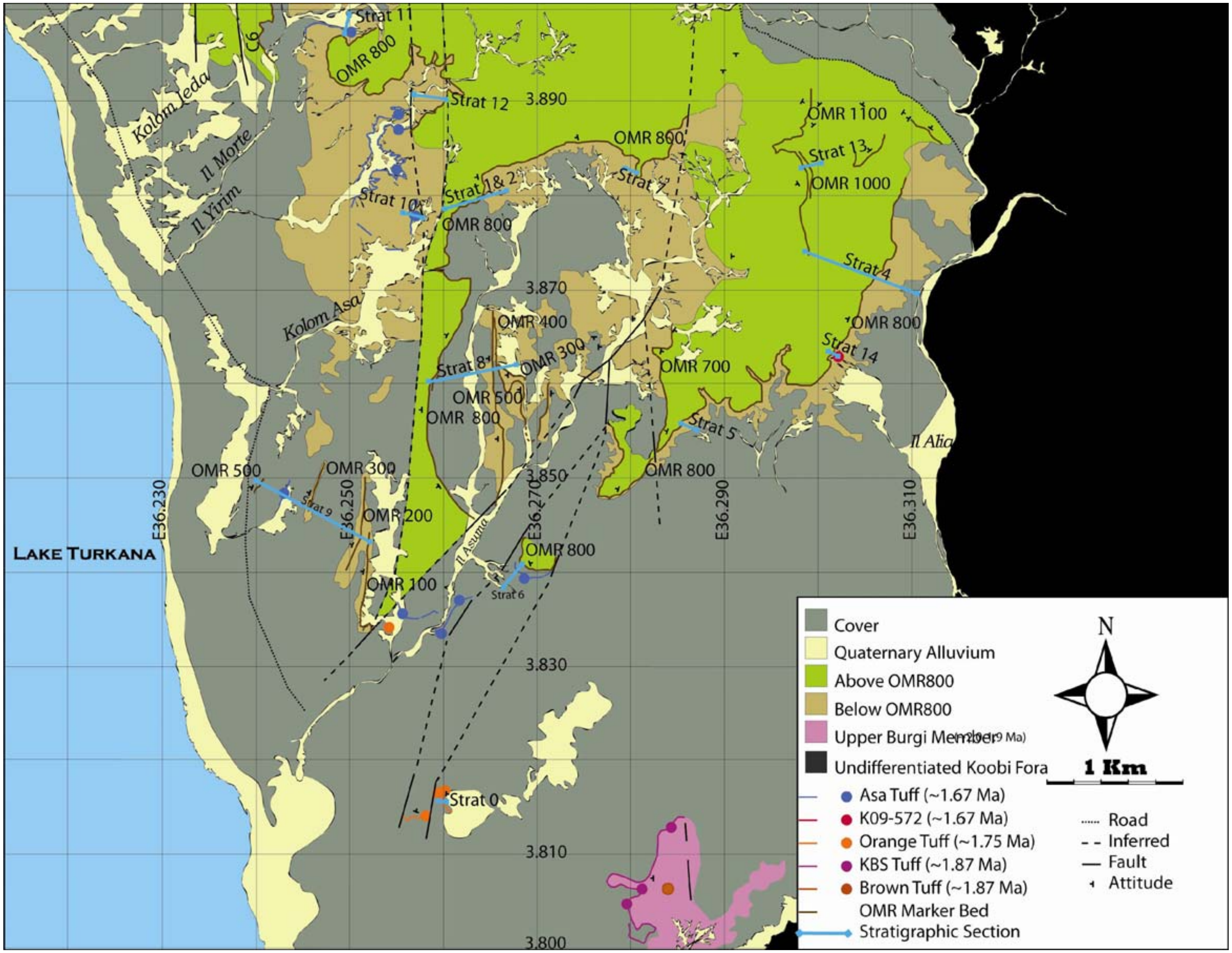
Cerling, 1982; Cerling and Brown, 1982; Brown and Feibel, 1986). This team was composed of T.E. Cerling and F.H. Brown and later C.S. Feibel. The new scheme replaced Bowen and Vondra's (1973) three formations with a single formation which they named the Koobi Fora Formation (Brown and Feibel, 1986). Many of the dates placed on the volcanic ash layers within the Koobi Fora Formation were controversial (e.g., Cook and Maglio, 1972; Brown et al., 1978) at the time. Due to this controversy new dates were needed, and they were provided by a team from the University of California, Berkeley (Cerling et al., 1979) and by Ian McDougall of the Australian National University (McDougall et al., 1980; McDougall et al., 1985a; Feibel et al. 1989; McDougall and Brown, 2006; McDougall and Brown, 2008).

The new scheme divides the Koobi Fora Formation's Pliocene and Pleistocene strata into eight members based on chemically distinctive volcanic ash marker horizons. From bottom to top these members are named: Lonyumun, Moiti, Lokochot, Tulu Bor, Burgi, KBS, Okote, and Chari. Detailed accounts of the old and new schemes are provided by Brown and Feibel (1986, 1991, and 1997).

5.2. This Study

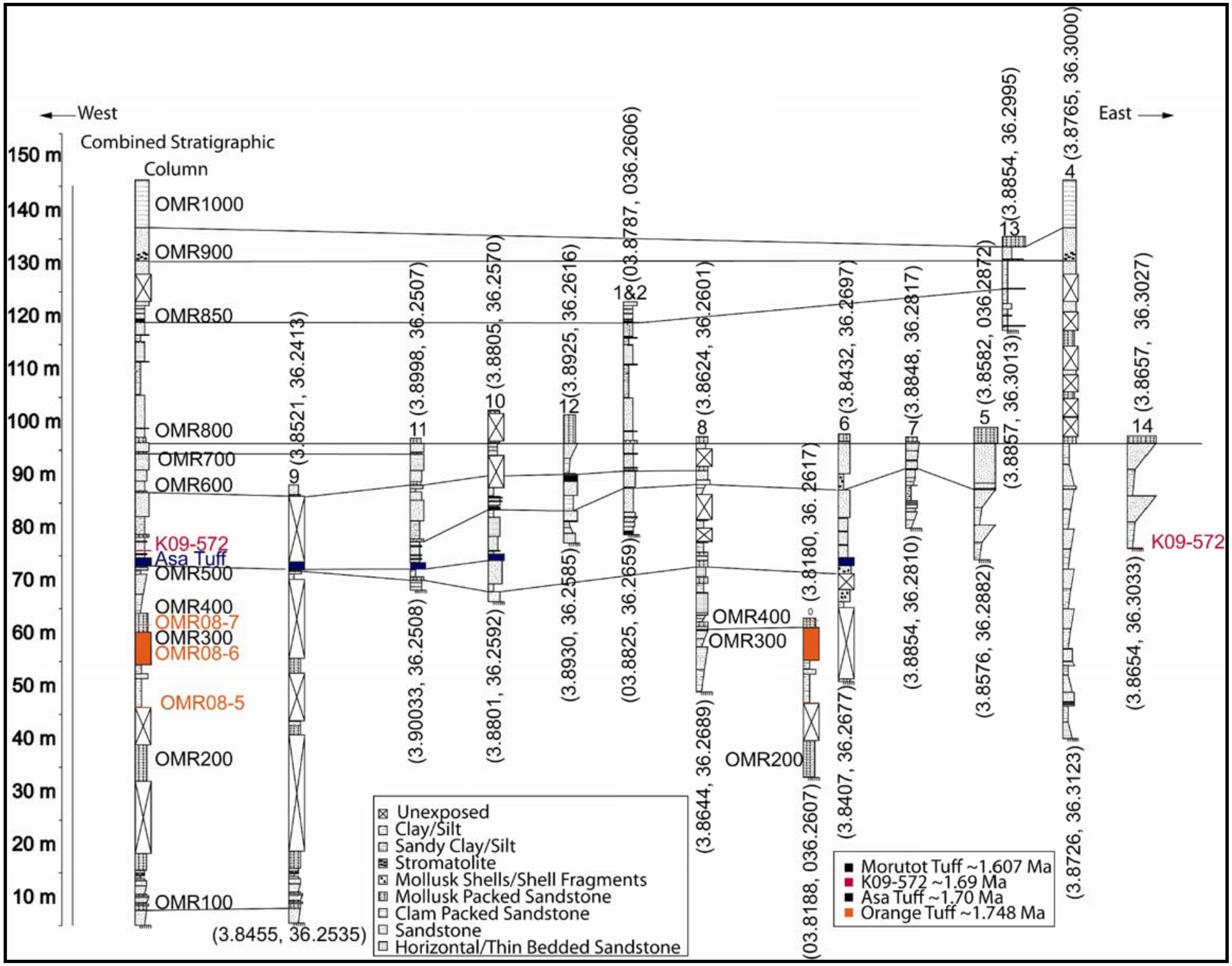
Two members of the Koobi Fora Formation, the upper Burgi Member (~2.0–1.9 Ma) and the KBS Member (~1.9–1.6 Ma), are exposed in the field area. Much of the field area is obscured by Quaternary alluvium and recent surficial cover such as wind blown sand. The KBS Member was mapped and measured stratigraphically, but the upper Burgi Member was only mapped due to poor exposure (Figures 6 and 7).

Figure 6. Geologic map of the KBS Member of the Koobi Fora Formation in paleontologic collecting Areas 106, 107 and 109.



Lake Turkana
Kolom Jeda
Il Morte
Il Yirim
Kolom Asa
Il Asuma
Il Alia
C6
Strat 11
OMR 800
Strat 12
3.890
OMR 800
Strat 7
OMR 1100
Strat 13
OMR 1000
Strat 10
Strat 1& 2
OMR 800
Strat 4
3.870
OMR 400
OMR 300
OMR 800
Strat 14
Strat 8
OMR 700
OMR 500
OMR 800
Strat 5
OMR 500
OMR 300
3.850
OMR 800
Strat 9
OMR 200
E36.230
E36.250
E36.270
E36.290
E36.310
OMR 800
OMR 100
Strat 6
3.830
Strat 0
3.810
3.800
N
1 Km
Cover
Quaternary Alluvium
Above OMR800
Below OMR800
Upper Burgi Member
Undifferentiated Koobi Fora
Asa Tuff (~1.67 Ma)
K09-572 (~1.67 Ma)
Orange Tuff (~1.75 Ma)
KBS Tuff (~1.87 Ma)
Brown Tuff (~1.87 Ma)
OMR Marker Bed
Stratigraphic Section
Road
Inferred
Fault
Attitude

Figure 7. Correlated stratigraphic columns measured in this study. The location of each section is shown in Figure 6 represented by labeled light blue lines.


West
East
Combined Stratigraphic Column
150 m
140 m
130 m
120 m
110 m
100 m
90 m
80 m
70 m
60 m
50 m
40 m
30 m
20 m
10 m
OMR1000
OMR900
OMR850
OMR800
OMR700
OMR600
K09-572
Asa Tuff
OMR500
OMR400
OMR08-7
OMR300
OMR08-6
OMR08-5
OMR200
OMR100
9 (3.8521, 36.2413)
(3.8455, 36.2535)
11 (3.8998, 36.2507)
(3.90033, 36.2508)
10 (3.8805, 36.2570)
(3.8801, 36.2592)
12 (3.8925, 36.2616)
(3.8930, 36.2585)
1&2 (03.8787, 036.2606)
(03.8825, 36.2659)
8 (3.8624, 36.2601)
(3.8644, 36.2689)
OMR400
OMR300
OMR200
(3.8180, 36. 2617)
(03.8188, 036.2607)
6 (3.8432, 36.2697)
(3.8407, 36.2677)
7 (3.8848, 36.2817)
(3.8854, 36.2810)
5 (3.8582, 036.2872)
(3.8576, 36.2882)
13 (3.8854, 36.2995)
(3.8857, 36.3013)
4 (3.8765, 36.3000)
(3.8726, 36.3123)
14 (3.8657, 36.3027)
(3.8654, 36.3033)
K09-572
Unexposed
Clay/Silt
Sandy Clay/Silt
Stromatolite
Mollusk Shells/Shell Fragments
Mollusk Packed Sandstone
Clam Packed Sandstone
Sandstone
Horizontal/Thin Bedded Sandstone
Morutot Tuff ~1.607 Ma
K09-572 ~1.69 Ma
Asa Tuff ~1.70 Ma
Orange Tuff ~1.748 Ma

5.3 Upper Burgi Member

The upper Burgi Member (~2.0–1.9 Ma) is the most widely exposed member of the Koobi Fora Formation (Feibel et al., 1991). This member was informally separated from the lower Burgi Member by Brown and Feibel (1986). The boundary was placed at a slight angular unconformity (or erosional disconformity) defined as the base of the upper Burgi Member. The upper limit of the upper Burgi Member is placed at the bottom of the KBS Tuff, the base of which is defined as the bottom of the KBS Member. Even though the upper Burgi Member is the most widely exposed member of the Koobi Fora Formation, it is only minimally exposed in the southern portion of the study area (Area 109) in very low lying outcrops composed of silty sandstone terraces draped by basalt gravel. Due to this minimal exposure, no attempt was made to establish a stratigraphic section for this unit in this area. A thorough discussion of the upper Burgi Member is given in the Koobi Fora Research Project, Volume 3, Chapters 1 and 6 by Brown and Feibel (1991). The KBS Member is the only member that has been stratigraphically studied, mapped, and described in Areas 106 and 107.

5.4 KBS Member

The KBS Member is the primary member exposed in the field area, making up all of the major outcrops and the vast majority of the mapped strata. Strata within this unit are dominated by claystones, siltstones, fine- to coarse-grained sandstones and mollusc-packed sandstones termed arenaceous bioclastic carbonates (ABCs) along with algal beds by Lepre et al. (2007). A single cryptalgal biolithite bed is also present.

Feibel (1983) defined algal beds, carbonate beds and tuffaceous beds in Areas 102 and 103, north of the study area. He numbered the algal beds using the designations A1 through A11 with A1 being the oldest and A11 the youngest. The same was done for the carbonate beds (C1–C6) and the tuffaceous beds (T1–T11). Figure 8 includes an excerpt of the applicable part of the composite stratigraphic column composed by Feibel (1983).

ABCs are easily mapped, providing stratigraphic and structural control. It is not possible to distinguish ABCs from each other based on the molluscs present or matrix due to lateral variations in their character. The only method that can be used to identify an ABC in one location as being the same as another in a different location is to measure a stratigraphic section through each and compare the sediment packages based on thickness and sequence. However, this method is flawed because lateral variation is common; for instance in some locations an ABC will appear as a single bed and in others it will appear as two or more beds (Figure 9). Another difficulty in identifying ABCs is that several studies used algal beds as markers (in Areas 102 and 103) and these algal beds are only laterally continuous over relatively small areas in many instances. Evidence that algal beds are location specific is that Feibel (1983) identified 11 primary algal beds within the KBS Member in Areas 102 and 103 whereas only one algal bed was found within the KBS Member in this study area. This suggests that the area to the north was more conducive to algal growth during KBS Member time.

Due to the variable nature of ABCs, it was difficult to piece together the stratigraphic columns measured in the field into a single composite section. Instead of using the A and C designations established by Feibel in Areas 102 and 103, mapped units in this thesis were designated by a separate number of the form OMRxxx after this authors initials followed by a number designation.

Figure 8. Composite stratigraphic column of Feibel (1983). Three lithologies are shown here, algal beds, carbonate beds and tuffaceous beds. The algal beds are labeled A1 through A6, the carbonate beds (C4–C6) and the tuffaceous beds (T4–T9). The unlabeled white sections represent other lithologies such as sandstones, siltstones and claystones.

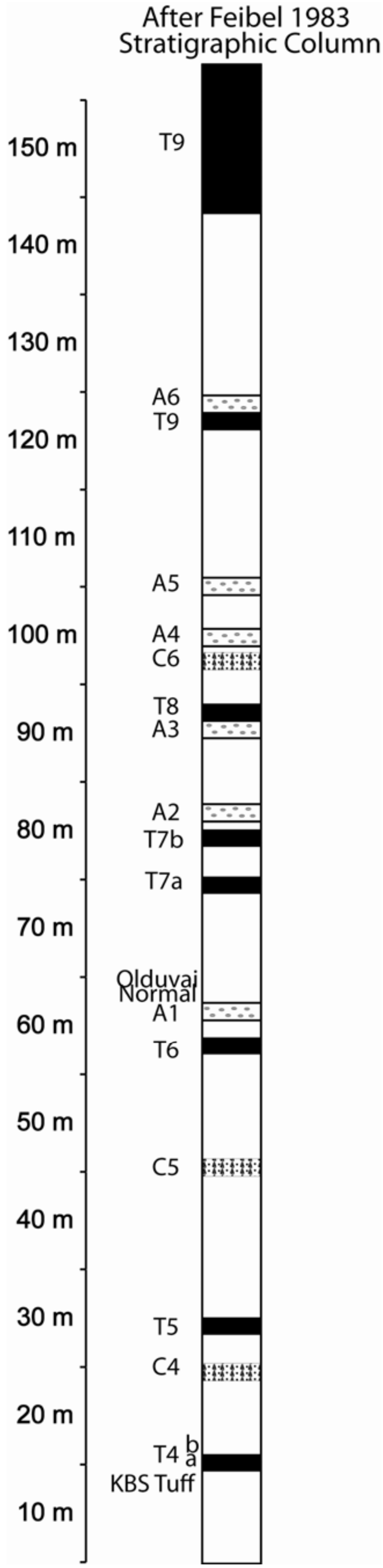

After Feibel 1983
Stratigraphic Column
150 m
140 m
130 m
120 m
110 m
100 m
90 m
80 m
70 m
60 m
50 m
40 m
30 m
20 m
10 m
T9
A6
T9
A5
A4
C6
T8
A3
A2
T7b
T7a
Olduvai
Normal
A1
T6
C5
T5
C4
T4 b
a
KBS Tuff

Figure 9. C6 in southern Area 103 exhibiting a split from a single bed to a double bed. Photograph taken standing on C6 toward the south-southwest at 3.9050 N, 36.2417 E.

The most prominent and most continuous bed is OMR800, which is interpreted to be equivalent to Feibel's C6. This unit is a very prominent mollusc-packed sandstone that has been disturbed only minimally by faulting. OMR 800 was correlated to C6 based on: 1) its presence directly across the valley of Il Morte with no evidence of faulting between; 2) its elevation being appropriate to coincide with the elevation of C6 after taking dip into account and; 3) comparison of the relative thicknesses of the sediment packages from this study's generalized stratigraphic column, and the composite stratigraphic column presented by Feibel (1983). OMR 800 was used as the primary bed in correlating ten of the thirteen measured stratigraphic sections. Of the three remaining sections, one was connected to the composite section using the Asa Tuff and another using the Orange Tuff. The final correlation was made using stratigraphic columns 4 and 13 because they were each measured through the algal bed OMR900 in two different locations (Figures 6 and 7)

5.5 KBS Tuff ~1.87 Ma

The KBS Tuff is found in the southern region of the study area in Area 109. The base of the KBS Tuff is the base of the KBS Member. McDougall and Brown (2006 and 2008) give 1.869 ± 0.021 Ma as the best estimate of the age of the KBS Tuff on the basis of $^{40}Ar/^{39}Ar$ dating. They standardized all ages using an age of 28.1 Ma for the Fish Canyon Sanidine monitor, so the age may need adjustment if the age of the Fish Canyon Sanidine is changed through new analyses.

The KBS Tuff is fine-grained and blue-gray. The washed sample before magnetic separation is approximately 90% glass and 10% feldspar and quartz. The glass shards are principally flat, stretched and bubble junction types, with a few pumiceous grains.

Shards are either brown (5%) or colorless (95%). The average chemical composition of the KBS Tuff is given in Table 1. Scanning electron microscope (SEM) images of representative glass shards are shown in Figure 10.

5.6 Brown Tuff ~1.87 Ma

According to Brown et al. (2006) the Brown Tuff is found stratigraphically between the airfall KBS Tuff and the later fluvially deposited KBS Tuff. This indicates that both the KBS and Brown Tuffs are approximately the same age.

The Brown Tuff is fine-grained and grey. The washed sample before magnetic separation is ~85% glass on average with the remaining 15% being composed primarily of feldspars and some pyroxene. Glass shards in the sample are flat with holes and bubble junctions; thicker shards are very pale brown in color. The average chemical composition of the Brown Tuff is given in Table 1. SEM images of representative glass shards are shown in Figure 11.

5.7 Orange Tuff ~1.748 Ma

The Orange Tuff (Figure 12) is located in the central and south central parts of the study area and is medium-grained and grey. The washed sample before magnetic separation is approximately 70% glass on average and 30% quartz, feldspar, green pyroxenes, magnetite and augite. Many of the glass shards have bubble junction morphology. Approximately 95% of the glass shards are colorless, whereas the remaining 5% are brown. SEM images of representative glass shards are shown in Figure 13. The average chemical composition of the Orange Tuff is given in Table 1.

Table 1. Average analyses of glass from samples of the Brown, KBS and Orange Tuffs collected in the study area.

Asa Tuff Sample	Mode	SiO_2	TiO_2	ZrO_2	Al_2O_3	*Fe_2O_3	MnO	MgO	CaO	BaO	Na_2O	K_2O	F	Cl	Sum	less O	Total	mp H_2O	Total	# Shards
Brown Tuff (~1.87 Ma)																				
OMR08-03	A	68.06	0.27	0.15	12.91	3.57	0.13	0.07	0.76	0.04	4.89	3.76	0.25	0.14	95.02	0.14	94.88	7.13	102.01	10
KBS Tuff (~1.87 Ma)																				
OMR08-04	A	72.70	0.19	0.17	10.64	2.93	0.10	0.04	0.18	0.00	4.43	3.56	0.32	0.19	95.45	0.18	95.27	6.64	101.92	10
OMR08-01	A	72.75	0.18	0.16	10.61	2.94	0.11	0.03	0.17	0.00	4.39	3.44	0.36	0.18	95.32	0.19	95.13	7.01	102.14	10
OMR08-02	A	72.32	0.17	0.18	10.59	2.99	0.11	0.03	0.18	0.00	4.38	3.68	0.34	0.18	95.15	0.18	94.96	7.12	102.08	10
Orange Tuff (~1.75 Ma)																				
OMR08-09	A	72.57	0.10	0.07	11.77	1.86	0.04	0.01	0.34	0.00	4.09	4.61	0.08	0.21	95.81	0.10	95.71	3.56	99.27	19
OMR08-11	A	72.93	0.09	0.07	11.87	1.92	0.05	0.01	0.33	0.00	4.31	4.29	0.05	0.21	96.18	0.09	96.09	2.87	98.96	14
OMR08-05	A	72.39	0.08	0.07	11.73	1.95	0.06	0.01	0.32	0.01	4.39	3.71	0.27	0.22	95.22	0.17	95.06	6.63	101.68	7
OMR08-05	A	72.94	0.09	0.07	11.74	1.81	0.03	0.01	0.32	0.00	4.28	3.77	0.21	0.22	95.53	0.16	95.38	5.24	100.61	17
OMR08-06	A	72.56	0.09	0.07	11.74	1.95	0.05	0.01	0.33	0.00	4.14	4.73	0.13	0.23	96.03	0.11	95.92	4.87	100.79	9
OMR08-07	A	72.48	0.09	0.07	11.74	1.84	0.04	0.01	0.33	0.00	4.12	4.41	0.12	0.21	95.60	0.12	95.48	4.20	99.69	14
OMR08-07	A	72.56	0.07	0.10	11.64	1.88	0.04	0.01	0.33	0.00	4.38	4.53	0.23	0.23	96.00	0.15	95.85	5.21	101.06	7
OMR08-09	A	73.20	0.09	0.07	11.78	1.99	0.06	0.01	0.35	0.01	3.92	4.91	0.10	0.23	96.71	0.09	96.62	4.36	100.98	9
OMR08-11	A	72.74	0.09	0.08	11.88	1.96	0.05	0.01	0.34	0.01	4.60	3.77	0.15	0.23	95.96	0.14	95.83	5.16	100.99	7
OMR08-05	B	64.75	0.37	0.13	14.57	3.45	0.11	0.22	1.08	0.00	4.70	5.25	0.21	0.09	94.93	0.11	94.82	6.88	101.70	3
OMR08-05	B	65.07	0.41	0.13	14.96	3.55	0.08	0.27	1.14	0.02	4.74	5.17	0.09	0.10	95.81	0.10	95.71	5.07	100.78	4
OMR08-06	B	65.40	0.30	0.11	14.31	3.26	0.10	0.13	0.96	0.00	4.70	5.57	0.21	0.11	95.17	0.11	95.06	6.31	101.37	1
OMR08-07	B	65.64	0.39	0.05	14.41	3.41	0.07	0.18	1.00	0.00	5.01	5.29	0.17	0.11	95.73	0.10	95.63	5.51	101.14	3
OMR08-07	B	66.02	0.32	0.14	14.74	3.34	0.11	0.23	1.04	0.00	5.01	5.35	0.06	0.11	96.53	0.08	96.45	3.23	99.68	2
OMR08-09	B	66.40	0.33	0.12	14.70	3.39	0.10	0.15	0.93	0.00	4.79	5.41	0.21	0.11	96.65	0.11	96.54	5.18	101.71	1
OMR08-11	B	66.20	0.33	0.09	14.45	3.29	0.07	0.16	0.97	0.00	4.94	5.09	0.06	0.11	95.85	0.08	95.77	3.36	99.13	6

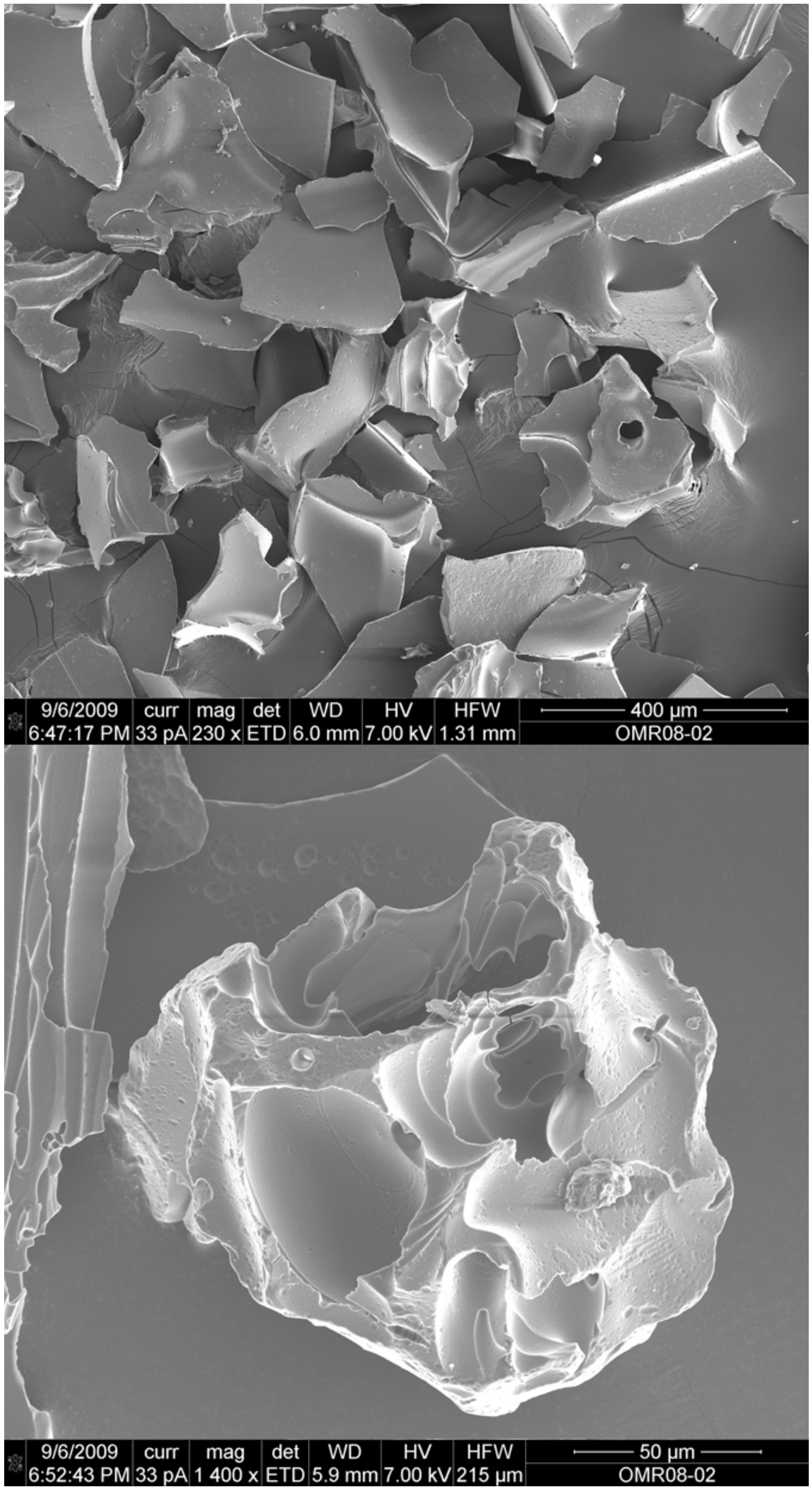


Figure 10. Scanning Electron Microscope images of glass shards from the KBS Tuff, sample OMR08-2.

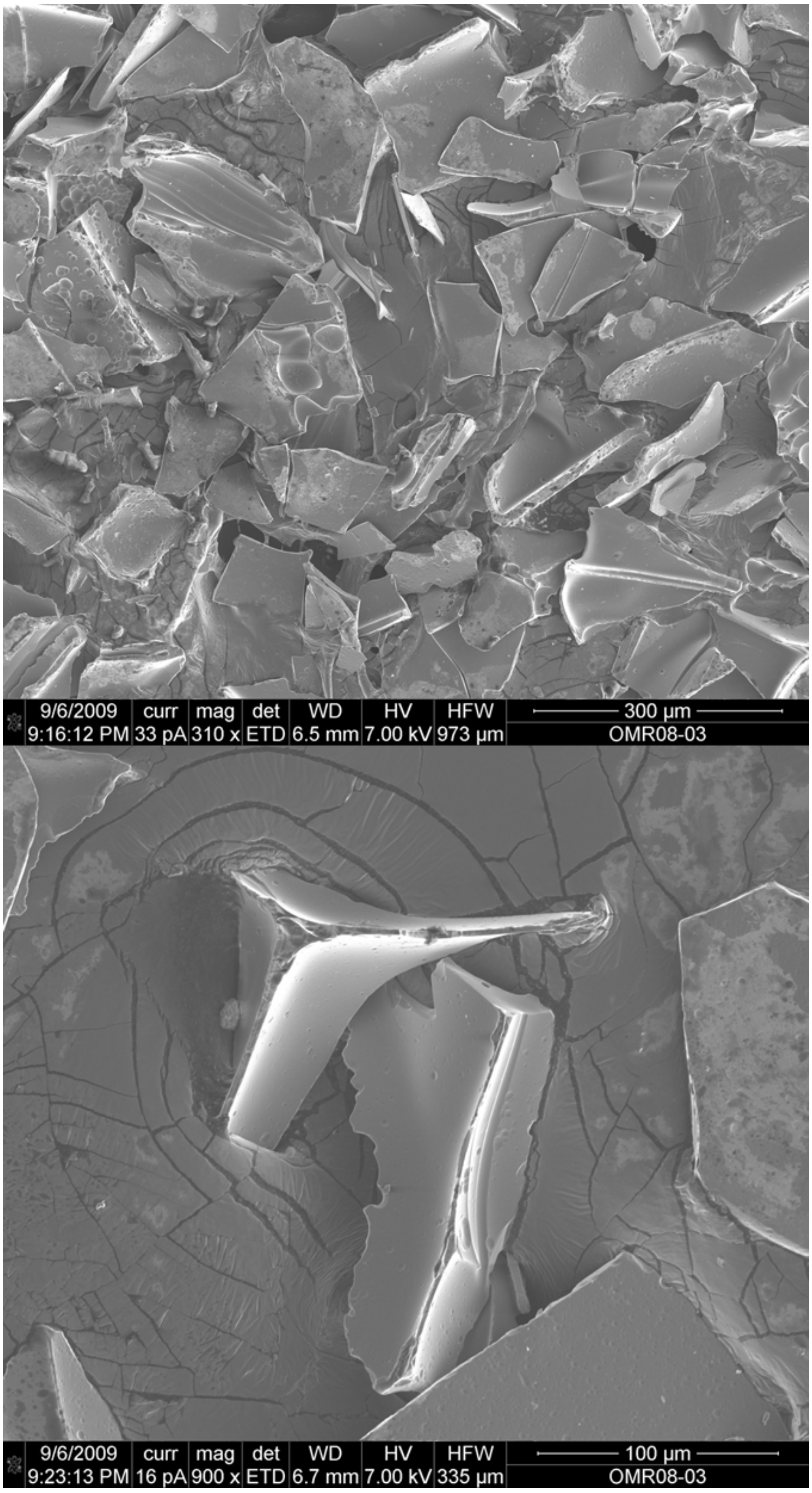


Figure 11 Scanning Electron Microscope images of glass shards from the Brown Tuff, sample OMR08-3.

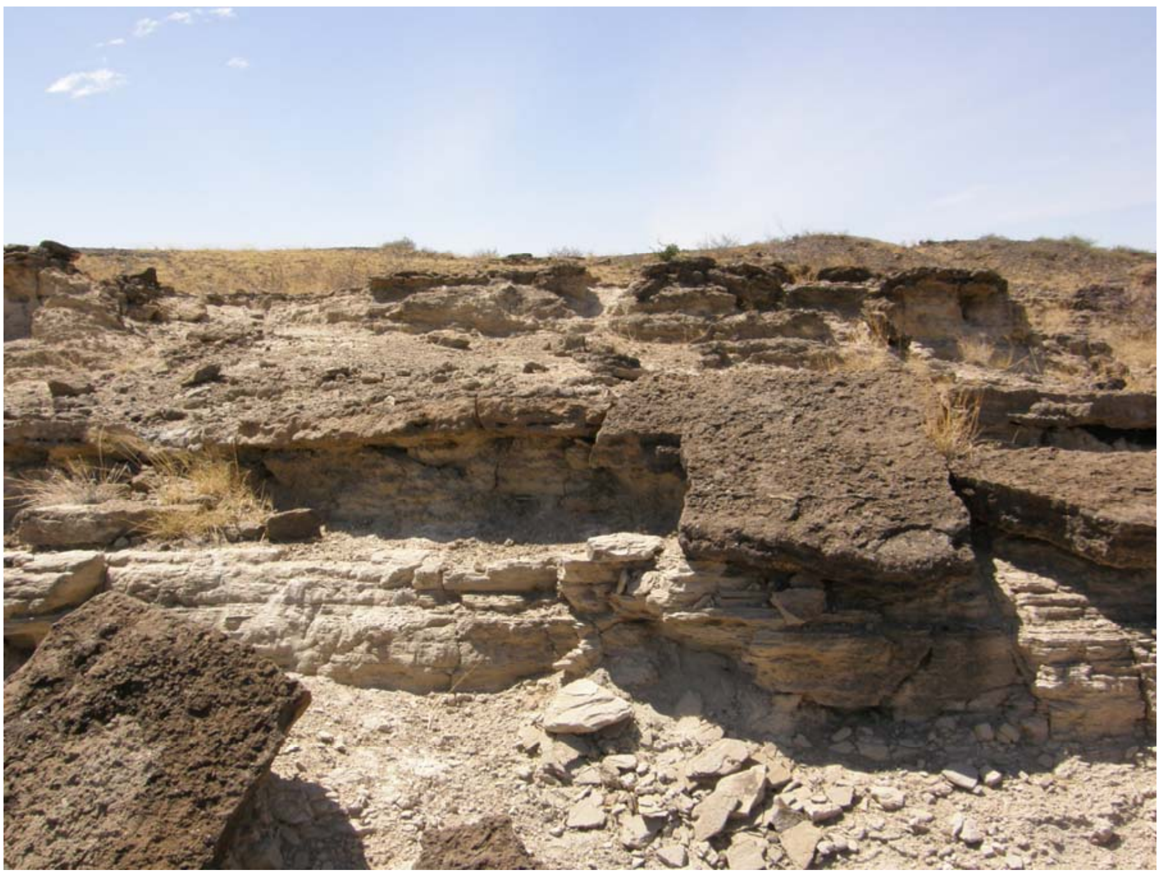


Figure 12. Orange Tuff with interbedded mollusc-packed sandstone layer.

The Orange Tuff correlates with the Kayle Tuff-1 of the Konso Formation and with Tuff J of the Shungura Formation in the lower Omo Valley. Katoh et al. (2000) dated the Kayle Tuff-2 (2.5 m above the Kayle Tuff-1) at 1.725 Ma using an age of 27.84 Ma for the Fish Canyon Sanidine monitor in their work. This causes the age of 1.725 Ma to be .09% low relative to the ages quoted for the Koobi Fora Formation thus recalculating the age so that it is consistent with ages reported for the Koobi Fora Formation yields 1.736 Ma (i.e., 1.72 Ma * 28.10/27.84 = 1.736 Ma). Based on this age in conjunction with the Olduvai Normal (1.778 Ma) which lies below the Orange Tuff an approximate age of 1.748 Ma is applied here.

5.8. Asa Tuff ~1.70 Ma

The Asa Tuff is defined here and is named after the type locality in Kolom Asa at 3.8805 N, 36.2583E. In this location the Asa Tuff is 1.25 m thick, blue grey, very fine-grained, vertically fractured and exhibits millimeter scale bedding. The average chemical composition of modes found within the Asa Tuff are recorded in (Tables 2, 3, 4 and 5). This tuff lies stratigraphically 21 m below OMR800 (C6) and about 15 m above the Orange Tuff.

The Asa Tuff is found in several other locations within the study area, and has an average thickness of approximately 1.5 m. In all locations, it is fine-grained, blue-grey horizontally bedded, and has pronounced vertical fractures dominating its structural fabric. The washed sample, before magnetic separation, is on average ~85% glass. The glass shards are mainly brown but some clear shards are also present. The remaining 15% of the samples are composed of quartz, feldspar, frothy pumice, green pyroxenes, augite, bleached biotite, blue green hornblendes and green brown amphiboles.

Table 2. Average analyses of modes A, B, and C of glass shards from the Asa Tuff.

Asa Tuff Sample	Mode	SiO_2	TiO_2	ZrO_2	Al_2O_3	*Fe_2O_3	MnO	MgO	CaO	BaO	Na_2O	K_2O	F	Cl	Sum	less O	Total	mp H_2O	Total	# Shards
K81- 550	A	70.08	0.35	0.28	9.51	5.48	0.29	0.12	0.17	0.00	2.10	2.23	0.16	0.16	91.06	0.16	90.90	8.38	99.28	15
K81-550 (Reanal)	A	70.20	0.34	0.29	9.41	5.50	0.29	0.11	0.17	0.00	2.10	2.23	0.16	0.16	91.09	0.16	90.93	8.35	99.28	14
OMR08-21	A	71.01	0.33	0.20	9.45	5.56	0.26	0.11	0.18	0.00	3.44	2.31	0.21	0.17	93.37	0.18	93.19	6.42	99.61	7
K82- 820	A	70.98	0.34	0.24	9.39	5.57	0.25	0.11	0.16	0.00	1.96	2.16	0.13	0.16	91.59	0.15	91.44	7.66	99.11	6
ETH08-240	A	71.76	0.32	0.22	9.45	5.59	0.23	0.09	0.21	0.00	1.01	2.67	0.16	0.16	91.87	0.10	91.77	7.52	99.29	3
K07-505	A	71.42	0.33	0.27	9.33	5.59	0.28	0.12	0.15	0.00	3.57	3.81	0.22	0.17	95.39	0.19	95.21	5.56	100.76	14
K07-505	A	71.45	0.33	0.26	9.32	5.59	0.28	0.12	0.14	0.00	3.64	3.56	0.21	0.16	95.20	0.18	95.02	5.34	100.36	15
OMR08-13	A	71.39	0.33	0.22	9.69	5.64	0.27	0.12	0.17	0.00	3.13	2.16	0.21	0.18	93.63	0.19	93.44	5.79	99.24	7
OMR08-16	A	71.64	0.32	0.24	9.73	5.65	0.26	0.10	0.16	0.00	4.62	4.51	0.15	0.17	97.69	0.16	97.53	2.28	99.81	3
OMR08-12	A	70.96	0.35	0.21	9.24	5.67	0.27	0.11	0.15	0.00	4.60	3.38	0.20	0.16	95.44	0.18	95.26	4.59	99.85	10
ETH08-240	A	71.73	0.35	0.23	9.36	5.77	0.27	0.11	0.18	0.00	2.95	2.89	0.27	0.16	94.41	0.21	94.20	6.26	100.46	9
K07-505	A	72.45	0.34	0.26	9.21	5.83	0.27	0.12	0.16	0.00	1.80	3.35	0.22	0.17	94.18	0.13	94.05	6.46	100.51	35
OMR08-21	B	71.23	0.34	0.23	9.50	4.98	0.21	0.11	0.16	0.00	3.41	2.23	0.20	0.16	92.88	0.17	92.71	6.72	99.43	18
OMR08-18	B	70.98	0.34	0.23	9.35	5.02	0.21	0.11	0.16	0.00	4.24	3.54	0.17	0.16	94.65	0.16	94.49	5.01	99.49	12
OMR08-12	B	71.75	0.34	0.22	9.36	5.16	0.21	0.11	0.15	0.00	4.43	3.05	0.21	0.14	95.26	0.17	95.09	5.09	100.17	8
K07-505	B	70.63	0.35	0.22	9.31	5.17	0.21	0.11	0.15	0.00	3.45	3.59	0.23	0.16	93.70	0.19	93.52	7.75	101.27	22
OMR08-12	C	63.47	0.87	0.09	15.19	3.49	0.14	0.58	0.83	0.00	5.65	4.64	0.09	0.05	95.18	0.09	95.10	5.73	100.83	2
ETH08-240	C	63.92	0.87	0.06	15.45	3.57	0.18	0.63	0.90	0.00	3.87	3.69	0.12	0.05	93.40	0.10	93.30	9.58	102.88	5
OMR08-12	C	65.26	0.75	0.08	14.65	3.63	0.16	0.51	0.62	0.00	5.40	4.01	0.08	0.04	95.29	0.08	95.21	5.62	100.83	7
K81-550	C	63.27	0.75	0.14	14.67	3.79	0.25	0.52	0.65	0.01	3.19	2.96	0.03	0.06	90.39	0.07	90.32	9.53	99.85	3
K82- 820	C	64.43	0.81	0.13	14.79	3.83	0.22	0.54	0.70	0.00	2.88	2.67	0.05	0.05	91.20	0.07	91.13	8.59	99.71	4
OMR08-21	C	65.26	0.79	0.12	14.67	3.92	0.20	0.50	0.62	0.00	4.16	2.95	0.09	0.06	93.44	0.09	93.35	7.00	100.34	2
OMR08-16	C	65.73	0.71	0.08	14.88	3.99	0.24	0.49	0.61	0.00	5.96	4.39	0.11	0.06	97.33	0.10	97.23	3.64	100.87	2
ETH08-240	C	64.87	0.90	0.08	14.57	4.02	0.22	0.64	0.86	0.00	2.79	2.90	0.14	0.05	92.14	0.11	92.03	8.20	100.24	4
ETH08-240	C	66.68	0.81	0.10	14.50	4.22	0.22	0.55	0.69	0.00	2.82	4.12	0.06	0.05	94.82	0.04	94.78	6.05	100.84	4
OMR08-24	D	72.21	0.18	0.31	9.91	3.51	0.11	0.04	0.17	0.00	3.60	1.27	0.19	0.20	91.77	0.16	91.61	6.69	98.30	2
ETH08-240	D	74.38	0.19	0.27	10.06	3.78	0.13	0.00	0.17	0.00	2.74	3.52	0.12	0.17	95.54	0.09	95.45	4.86	100.31	2

*All iron expressed as Fe_2O_3.

Table 3. Average analyses of modes E, F, G and H of glass shards from the Asa Tuff

Asa Tuff Sample	Mode	SiO_2	TiO_2	ZrO_2	Al_2O_3	$*Fe_2O_3$	MnO	MgO	CaO	BaO	Na_2O	K_2O	F	Cl	Sum	less O	Total	mp H_2O	Total	# Shards
OMR08-22	E	70.45	0.43	0.17	11.87	4.73	0.24	0.20	0.22	0.00	2.94	1.19	0.16	0.13	92.84	0.14	92.70	6.98	99.68	2
OMR08-21	E	68.85	0.49	0.15	11.89	4.82	0.24	0.27	0.28	0.00	3.56	2.39	0.19	0.12	93.36	0.16	93.20	6.69	99.89	5
OMR08-13	E	68.38	0.48	0.20	11.61	4.95	0.21	0.26	0.26	0.00	5.37	3.83	0.19	0.13	96.00	0.16	95.84	4.43	100.26	2
OMR08-16	F	72.96	0.18	0.15	10.66	2.71	0.06	0.03	0.17	0.00	4.32	4.39	0.16	0.16	96.03	0.13	95.89	3.80	99.69	3
OMR08-24	F	74.10	0.19	0.16	10.76	2.94	0.08	0.03	0.19	0.00	4.57	3.48	-0.01	0.18	96.73	0.07	96.67	2.74	99.41	5
K81-596	F	72.30	0.20	0.20	10.86	3.00	0.12	0.04	0.19	0.02	4.11	3.78	0.06	0.18	95.12	0.10	95.02	4.99	100.02	16
K80-157 M1	F	73.92	0.19	0.26	10.86	3.04	0.11	0.04	0.18	0.01	4.22	4.03	0.02	0.18	97.15	0.08	97.06	3.72	100.79	12
OMR08-15	F	74.89	0.13	0.19	10.65	3.06	0.11	0.05	0.16	0.00	4.07	4.52	0.06	0.18	98.06	0.07	98.00	1.91	99.91	2
K81- 596	F	75.01	0.16	0.13	10.64	3.11	0.14	0.03	0.17	0.02	3.80	3.93	-0.07	0.18	97.33	0.04	97.29	2.96	100.25	11
OMR08-18	F	76.30	0.25	0.21	10.68	3.14	0.11	0.04	0.19	0.00	3.74	4.34	0.00	0.19	99.19	0.05	99.14	1.27	100.42	4
OMR08-23	F	76.09	0.19	0.17	10.84	3.17	0.12	0.04	0.18	0.01	3.90	3.68	0.04	0.18	98.60	0.06	98.54	1.65	100.19	10
OMR08-15	F	73.73	0.19	0.17	10.85	3.20	0.10	0.03	0.17	0.00	4.03	3.70	0.15	0.19	96.60	0.14	96.46	3.55	100.01	5
OMR08-23	F	74.85	0.20	0.15	11.32	2.93	0.13	0.08	0.11	0.00	4.46	3.58	0.14	0.21	98.23	0.13	98.09	2.69	100.78	2
OMR08-18	F	74.87	0.15	0.18	11.22	2.99	0.10	0.05	0.19	0.00	4.41	3.72	0.01	0.18	98.15	0.08	98.07	2.13	100.20	3
OMR08-22	F	73.89	0.18	0.16	11.27	2.99	0.13	0.04	0.18	0.00	3.84	2.52	0.07	0.18	95.51	0.10	95.41	4.28	99.69	2
OMR08-24	F	74.22	0.20	0.15	10.94	3.02	0.09	0.02	0.20	0.00	4.58	3.46	0.05	0.18	97.19	0.09	97.10	3.09	100.19	7
K80-157 M1	F	74.08	0.19	0.27	10.93	3.04	0.11	0.04	0.17	0.01	4.21	3.75	0.01	0.17	97.04	0.07	96.97	3.40	100.37	14
OMR08-18	G	70.28	0.38	0.21	10.35	4.57	0.18	0.18	0.22	0.00	5.10	4.71	0.09	0.13	96.51	0.11	96.39	3.74	100.13	2
K80-157 M2	G	70.34	0.37	0.22	10.89	4.73	0.24	0.19	0.24	0.00	2.30	2.01	0.18	0.13	91.94	0.15	91.79	8.40	100.19	10
OMR08-24	G	70.51	0.37	0.21	10.47	4.83	0.19	0.19	0.22	0.00	3.23	1.29	0.12	0.13	91.87	0.13	91.75	7.21	98.96	9
K80-157 M2	G	70.53	0.34	0.21	10.51	4.94	0.26	0.18	0.21	0.01	2.30	1.98	0.17	0.14	91.89	0.15	91.74	8.38	100.12	5
OMR08-23	G	71.42	0.38	0.22	10.44	5.06	0.24	0.19	0.20	0.00	1.39	1.24	0.18	0.13	91.08	0.11	90.97	7.02	97.99	6
OMR08-24	G	71.19	0.39	0.20	10.73	5.12	0.25	0.17	0.21	0.00	3.30	1.55	0.22	0.14	93.59	0.18	93.41	6.03	99.44	2
K82- 820	G	69.90	0.38	0.30	10.67	5.17	0.22	0.18	0.21	0.02	2.29	2.40	0.14	0.13	92.13	0.14	91.99	7.69	99.67	3
K81- 596	H	70.21	0.35	0.22	11.18	4.20	0.22	0.15	0.29	0.01	2.24	2.68	-0.10	0.13	91.87	0.03	91.84	6.96	98.80	4
OMR08-24	H	71.57	0.35	0.20	11.06	4.47	0.20	0.10	0.27	0.00	3.72	2.19	0.13	0.15	94.50	0.13	94.37	4.98	99.34	3

*All iron expressed as Fe_2O_3.

Table 4. Average analyses of modes I, J, and K of glass shards from the Asa Tuff.

Asa Tuff Sample	Mode	SiO_2	TiO_2	ZrO_2	Al_2O_3	*Fe_2O_3	MnO	MgO	CaO	BaO	Na_2O	K_2O	F	Cl	Sum	less O	Total	mp H_2O	Total	# Shards
OMR08-16	I	69.59	0.42	0.18	10.70	4.37	0.17	0.20	0.25	0.00	4.39	3.19	0.14	0.11	93.81	0.13	93.68	5.93	99.61	7
OMR08-14	I	69.81	0.43	0.18	10.92	4.59	0.19	0.22	0.23	0.00	4.02	2.54	0.17	0.11	93.51	0.15	93.37	6.80	100.17	12
K82- 820	I	68.71	0.45	0.22	11.03	4.82	0.22	0.22	0.24	0.00	2.21	2.38	0.07	0.13	90.81	0.11	90.70	8.20	98.90	7
OMR08-23	I	71.33	0.40	0.17	11.19	4.86	0.23	0.18	0.22	0.00	3.21	1.51	0.20	0.13	93.74	0.16	93.58	6.21	99.78	4
OMR08-15	I	68.98	0.46	0.13	11.22	5.12	0.20	0.24	0.23	0.00	5.05	4.00	0.12	0.12	95.98	0.13	95.85	4.63	100.49	2
OMR08-14	I	69.47	0.41	0.18	11.00	5.12	0.25	0.22	0.23	0.00	4.69	3.62	0.15	0.13	95.59	0.15	95.45	5.13	100.58	4
OMR08-15	I	71.46	0.47	0.19	10.59	5.21	0.22	0.23	0.22	0.00	4.01	4.33	0.14	0.12	97.18	0.09	97.10	3.39	100.49	3
OMR08-18	J	67.27	0.57	0.12	12.69	4.00	0.17	0.33	0.34	0.00	5.53	5.07	0.11	0.08	96.37	0.10	96.26	3.74	100.00	6
OMR08-14	J	67.45	0.59	0.12	12.62	4.07	0.20	0.33	0.35	0.00	5.13	3.57	0.13	0.09	94.74	0.12	94.63	6.19	100.82	4
OMR08-12	J	68.12	0.51	0.11	12.95	4.24	0.19	0.31	0.32	0.00	5.35	3.00	0.17	0.08	95.46	0.13	95.32	5.61	100.94	2
OMR08-14	J	67.56	0.60	0.13	12.95	4.44	0.23	0.34	0.39	0.00	4.92	3.98	0.12	0.08	95.85	0.11	95.73	5.26	100.99	4
OMR08-15	J	68.80	0.55	0.15	12.78	4.48	0.21	0.34	0.40	0.00	2.50	2.72	0.16	0.09	93.18	0.09	93.09	6.43	99.53	7
OMR08-16	J	68.05	0.55	0.12	12.96	4.56	0.23	0.32	0.33	0.00	5.54	4.96	0.13	0.09	97.97	0.12	97.85	2.44	100.29	6
OMR08-15	J	69.09	0.51	0.16	12.40	4.79	0.22	0.27	0.33	0.00	5.08	4.87	0.11	0.09	98.04	0.11	97.93	2.66	100.59	2
K81-550	K	64.85	0.60	0.14	13.92	4.13	0.25	0.36	0.44	0.00	2.80	2.66	0.08	0.07	90.40	0.09	90.31	9.56	99.87	3
OMR08-14	K	65.73	0.69	0.07	14.18	4.16	0.22	0.42	0.51	0.00	5.33	3.35	0.14	0.07	94.98	0.12	94.86	6.21	101.08	3
OMR08-14	K	65.93	0.63	0.05	13.65	4.20	0.24	0.45	0.50	0.00	4.71	3.03	0.14	0.07	93.70	0.12	93.58	6.91	100.49	2
OMR08-15	K	67.80	0.72	0.09	13.76	4.24	0.20	0.46	0.49	0.00	2.51	2.57	0.11	0.09	93.02	0.06	92.95	6.81	99.76	2
OMR08-15	K	66.89	0.64	0.16	13.59	4.25	0.22	0.38	0.46	0.00	4.83	3.41	0.13	0.08	95.16	0.12	95.04	5.40	100.44	3

*All iron expressed as Fe_2O_3.

Table 5. Average analyses of modes L, M, N, O, P and Q of glass shards from the Asa Tuff.

Asa Tuff Sample	Mode	SiO_2	TiO_2	ZrO_2	Al_2O_3	$^*Fe_2O_3$	MnO	MgO	CaO	BaO	Na_2O	K_2O	F	Cl	Sum	less O	Total	mp H_2O	Total	# Shards
OMR08-18	L	66.26	0.63	0.07	13.75	3.78	0.19	0.39	0.46	0.00	5.65	5.47	0.16	0.08	96.98	0.12	96.85	3.48	100.33	3
OMR08-14	L	66.47	0.62	0.11	13.59	3.79	0.19	0.37	0.47	0.00	5.53	4.19	0.08	0.07	95.57	0.09	95.48	5.62	101.11	3
OMR08-12	L	66.45	0.66	0.13	13.90	3.84	0.17	0.40	0.44	0.00	5.17	4.22	0.16	0.07	95.69	0.12	95.57	4.81	100.38	3
OMR08-16	L	66.53	0.67	0.11	13.23	3.93	0.17	0.39	0.47	0.00	5.09	3.57	0.10	0.08	94.44	0.10	94.34	6.03	100.36	10
ETH08-240	M	71.84	0.34	0.29	10.11	4.83	0.22	0.13	0.22	0.00	1.14	3.00	0.14	0.16	92.42	0.10	92.32	7.53	99.86	2
K81- 596	N	70.11	0.37	0.17	10.00	5.08	0.28	0.18	0.20	0.00	1.06	1.78	-0.12	0.13	89.37	0.03	89.34	8.90	98.24	4
K81-596	O	69.80	0.28	0.25	10.89	3.79	0.18	0.09	0.28	0.00	3.73	3.40	0.07	0.15	93.02	0.10	92.92	6.68	99.60	3
ETH08-240	P	74.59	0.29	0.27	10.09	4.18	0.15	0.11	0.18	0.00	3.00	4.00	0.24	0.16	97.25	0.14	97.12	3.82	100.94	2
ETH08-240	Q	74.42	0.18	0.05	11.93	1.76	0.06	0.06	0.33	0.01	2.61	3.47	0.09	0.11	95.08	0.06	95.02	5.59	100.61	2

*All iron expressed as Fe_2O_3.

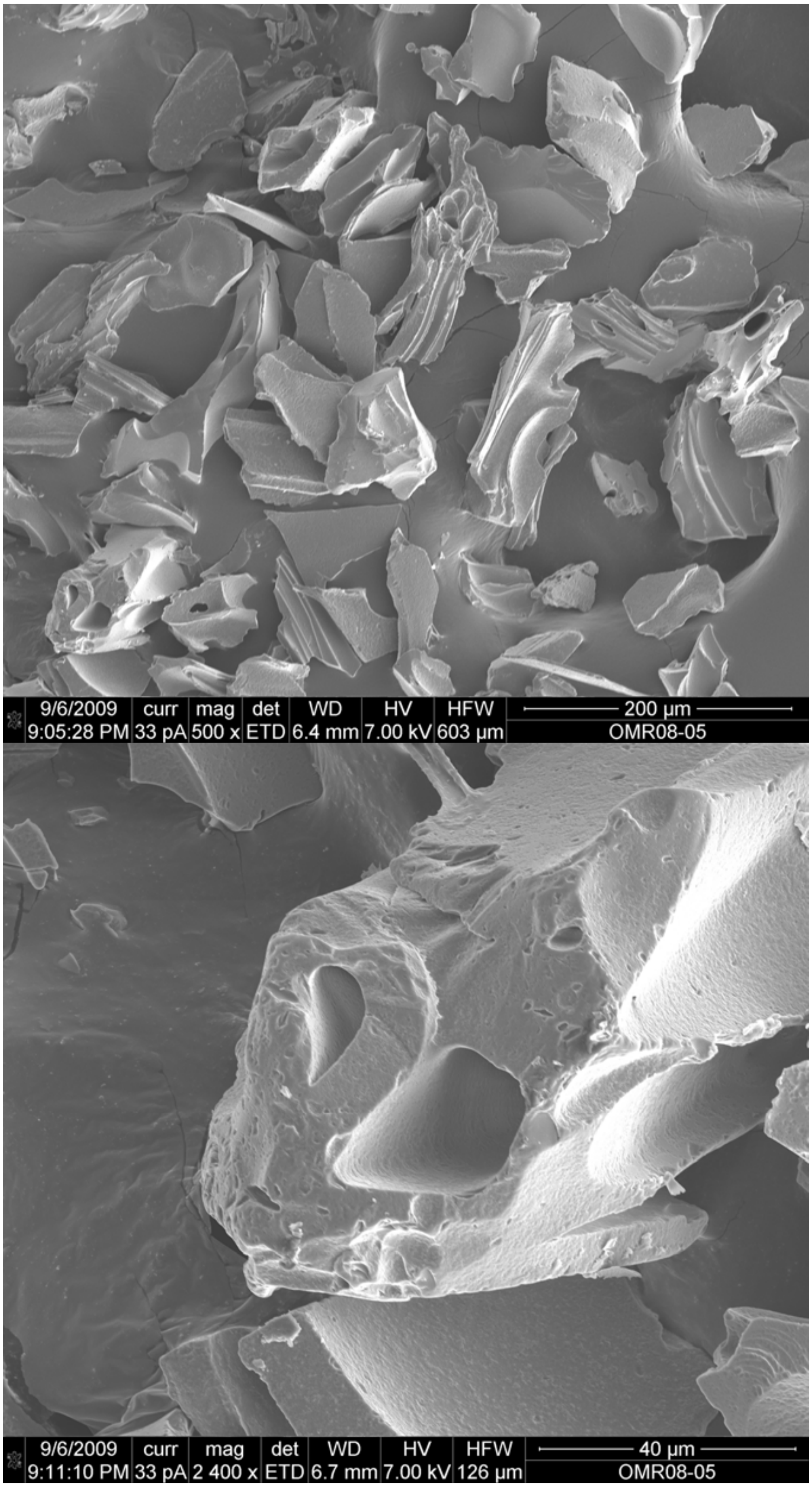


Figure 13. Scanning Electron Microscope images of glass shards from the Orange Tuff, sample OMR08-5.

Sponge spicules (both amphioxea and amphistrongyla) were also noted; Gathogo et al. (2008) assign amphistrongyla from exposures of the Koobi Fora Formation at Loiyangalani to *Potamophloios* sp., and those in the Orange Tuff are morphologically similar. The glass shards are flat, stretched and exhibit bubble junctions. SEM images of representative glass shards can be seen in Figure 14.

During this study, 10 samples of the Asa Tuff were collected and analyzed. In the past F.H. Brown collected five samples of the same unit but did not name the tuff or publish analyses of it.

After combining analyses of the samples collected in this study with analyses of the five earlier samples, the analyses were divided into compositional modes. These modes were separated from each other as explained above.

Seventeen compositional modes are believed to be recognizable within the Asa Tuff. Five of these modes probably represent reworked shards from older tuffs. The presence of the other twelve modes indicates that the tuff contains glass shards either from several eruptions at about the same time, or from a single eruption with quite different magmatic liquid compositions within it. Examination of the modes present within each samples and assuming that an earlier erupted mode can be present in a sample containing modes from a later eruption, it was possible to break the modes into chronologic order of formation (Table 6).

The Asa Tuff correlates with sample ETH08-240 from exposures of Member J in the Type area of the Shungura Formation which lies 30 m above the base of Tuff J. Like the Orange Tuff, this correlation is significant because it links the Shungura Formation to the Koobi Fora Formation. Correlation of the Asa Tuff to the Shungura Formation is

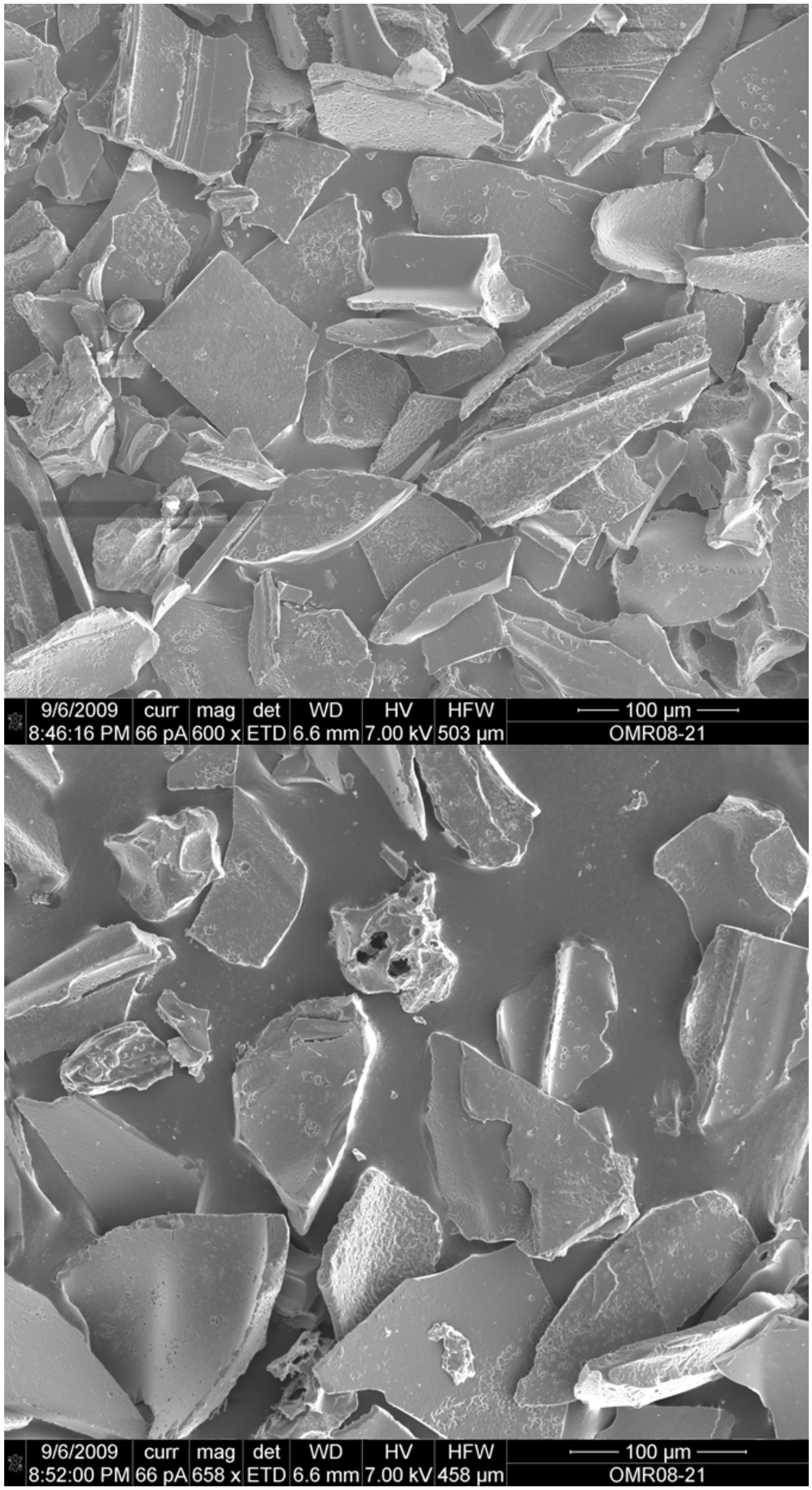


Figure 14. Scanning Electron Microscope images of glass shards from the Asa Tuff, sample OMR08-21.

Table 6. Breakdown of the modes present within the Asa Tuff arranged in chronologic order of eruption from bottom to top. The numbers in the boxes represent the number of glass shards found to be the composition of each mode from the listed sample.

Eruption	Sample	Modes:	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
6: Mode L	OMR08-23, 22, 18	**# Shards:**		12		2	2	31	8	3	4	6		3	Older Reworked Shards				
6: Mode L	OMR08-12	**# Shards:**	10	8	9							2		3					
6: Mode L	K81-550, K82-820, OMR08-16	**# Shards:**	38		9			3	3		14	6	3	**10**					
5: Mode I,J,K	OMR08-15, OMR08-14	**# Shards:**						7			**21**	**17**	**5**						
4: Mode F,G,H	K81-596, K80-157, OMR08-24	**# Shards:**				2		**65**	**26**	**7**						4	3		
3: Mode E	OMR08-13,21	**# Shards:**	21	18	2		**2**												
2: Mode C,D	ETH08-240	**# Shards:**	12		**13**	**2**									2			2	2
1: Mode A,B	K07-505	**# Shards:**	**64**	**22**															

especially important because the Orange Tuff is also present there. This allows a correlation between the stratigraphy within the Shungura, Konso, Nachukui and Koobi Fora Formations (Figure 15).

5.9. K09-572

The tuff represented by sample K09-572 lies below OMR800 and is interpreted, from its stratigraphic distance below OMR 800 (~20 m), to lie at a stratigraphic level above OMR500. Because it is pervasively altered, very few glass shards could be extracted. Approximately 1 kg of material was needed to extract less than a gram of glass, feldspar emerald green pyroxenes, garnets and magnetite. The average chemical composition of the volcanic glass is given in Table 7; it can be divided into two modes, neither of which correlate with any other tuff yet analyzed from the Koobi Fora Formation.

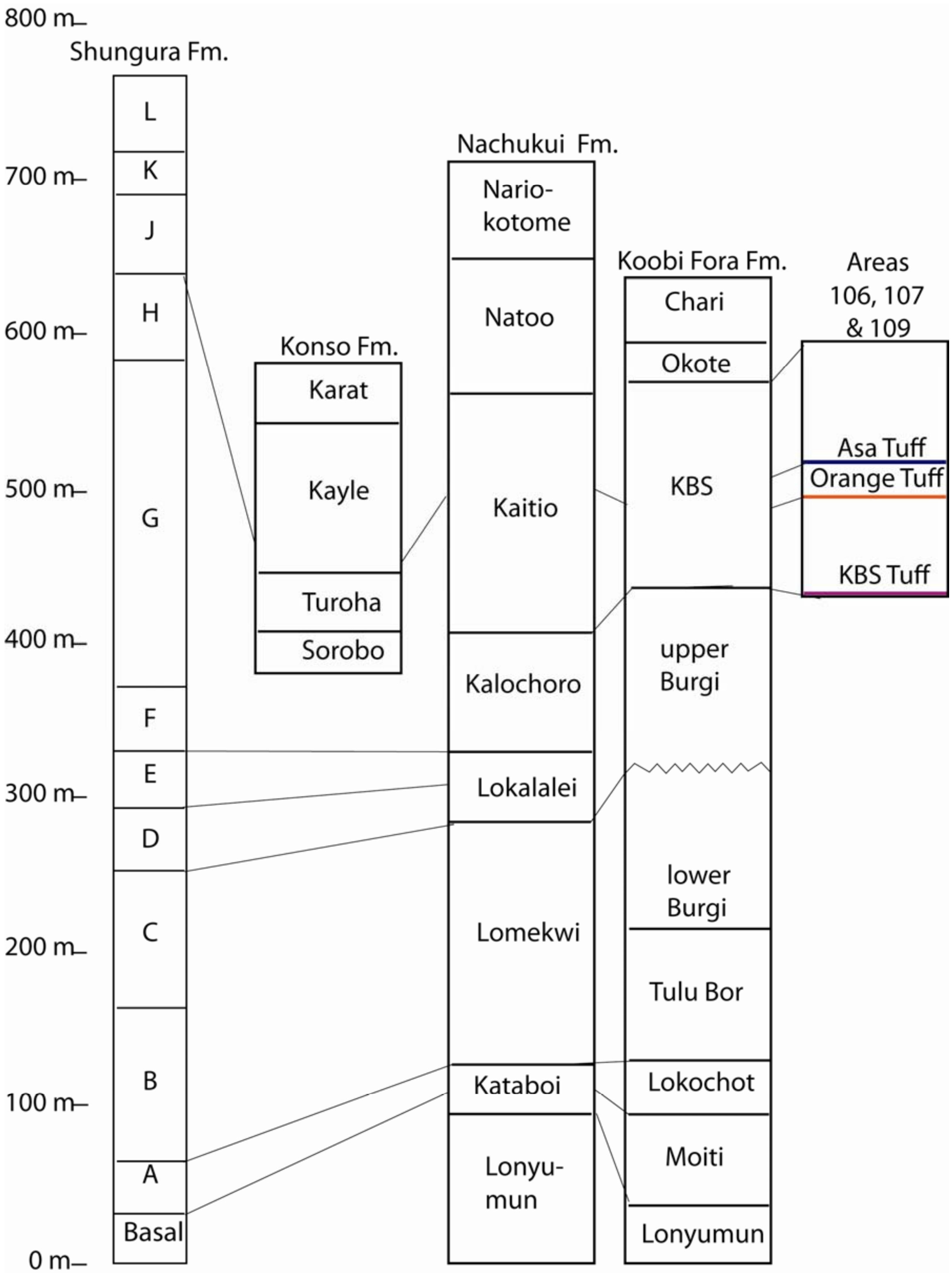


Figure 15. Correlation of the stratigraphy measured in this study to the Koobi Fora, Nachukui, Konso and Shungura Formations.

Table 7. Average analyses of the two modes of glass shards in sample K09-572.

Asa Tuff Sample	Mode	SiO_2	TiO_2	ZrO_2	Al_2O_3	*Fe_2O_3	MnO	MgO	CaO	BaO	Na_2O	K_2O	F	Cl	Sum	less O	Total	mp H_2O	Total	# Shards
k09-572	A	75.61	0.2	0.16	10.43	3.60085	0.16	0.034	0.148	0.001	1.613	2.919	0.238	0.177	95.29	0.14	95.15	5.85286	101	9
k09-572	B	76.12	0.17	0.02	11.79	0.86031	0.04	0.1	0.637	0.006	1.988	5.553	0	0.197	97.48	0.045	97.44	4.4419	101.88	2

*All iron expressed as Fe_2O_3.

6. DISCUSSION

The KBS Member, although not known by that name at the time, was originally investigated by Bruce Bowen in 1968 and 1969 in Areas 101, 102, and 103 (Figure 2). Later it was reinvestigated by R. G. H. Raynolds, G. Hahn, and G. Johnson in 1972 (e.g. Raynolds, 1972; Hahn et al., 1973a,b) resulting in an unpublished report and geologic section. Later the same section was again worked on by T.E. Cerling (1976), and still later by C.S. Feibel (1983). The latter author produced a composite section for Areas 102 and 103, closely similar to those provided by Raynolds (1972) and by Cerling (1977).

The base of the KBS Member is defined as the base of the KBS Tuff, and the top of the KBS Member is defined as the base of the Okote Tuff (Brown and Feibel, 1986). Because the KBS Tuff is present in Areas 102, 103, 110, etc. there is no difficulty with placement of the base of the member in sections in these areas. That is not the case for the top of the member because the Okote Tuff is known with certainty only from its type locality in Area 131 on the Karari Ridge (see Brown et al. (2006) for discussion). For this reason many workers have placed the local top of the KBS Member at the base of the Koobi Fora Tuff Complex (KFTC) in Area 103.

Lithostratigraphically, this is a reasonable placement because the KFTC is an easily recognizable unit in Area 103, although a definition of what bed is used as the base should be given because several thin tuffs lie below the principal package of tuffaceous strata ascribed to the KFTC. Originally Brown and Feibel (1986) had made lithostratigraphic divisions of the Koobi Fora Formation based on key beds (i.e., volcanic ash layers) that were recognizable on the basis of their chemical composition. They assumed that these units would be present in enough sections that members of the formation would be paraisochronous units—that is, units including the same intervals of geologic time. This has proven to be the case over most areas for most units, but the Okote Tuff is not one of them; complicating stratigraphic relationships.

Brown et al. (2006) and Brown and Feibel (1985) have shown that the Black Pumice Tuff lies above the type Okote Tuff in the section in Area 131 along the Karari Ridge. In the Ileret Area, the Black Pumice Tuff lies ~1m below the Lower Ileret Tuff, which is dated at 1.527 +/- 0.02 Ma, and thus has an age of ~1.53 Ma. In Area 103, the Black Pumice Tuff lies near the base of the KFTC, which thus has a similar age. In Area 131, the Black Pumice Tuff lies above the type Okote Tuff, which must therefore be older than 1.53 Ma. A maximum age of the type Okote Tuff is given by its placement above the lower Okote Tuff which contains pumices derived from the Morutot Tuff dated at 1.607 Ma (McDougall and Brown, 2006). Thus the age of the base of the KFTC must lie between 1.53 and 1.607 Ma, and has been taken to be 1.55 Ma by Lepre et al. (2007), although an age of 1.57 Ma would be just as defensible. The age interval spanned by the KBS Member is therefore 1.869 (the age of the KBS Tuff) to approximately 1.55 Ma (or arguably 1.57 Ma)

In the study area, no tuffs that lie within the KFTC have been identified. Instead four other tuffs have been identified: the KBS Tuff, the Brown Tuff, the Orange Tuff, and the Asa Tuff (defined here). The Orange Tuff has been correlated with Tuff J of the Shungura Formation and the Kayle Tuff-1 at Konso. The Kayle Tuff-2 (2.5 m above the

Kayle Tuff-1) is dated at 1.725 ± 0.03 Ma by Katoh (2000) using an age of 27.84 Ma for the Fish Canyon Sanidine monitor in which makes the age of 1.725 .09% low relative to the ages quoted for the Koobi Fora Formation thus an age between 1.735 and 1.61 should be applied to the Orange Tuff in this context. In the Nachukui Formation, west of Lake Turkana, the Asa Tuff lies below the Morutot Tuff, hence its age is also between 1.735 and 1.61 Ma and must be younger than the Orange Tuff. Tuff J is known to lie above the top of the Olduvai Event, for which the current age estimate is 1.778 Ma (Gradstein, Ogg and Smith, 2004). See Table 8 for a schematic representation of tuff correlations between the Koobi Fora, Shungura, Nachukui and Konso Formations near this stratigraphic level.

Lepre et al. (2007) used stratigraphic scaling, and a model of deposition that relies on ages of climatic events recorded in marine cores to suggest ages for prominent bioclastic sandstones in Areas 102 and 103. These ages range from 1.81 to 1.66 Ma, and the challenge here is to correlate their bioclastic units with similar units observed in the study area.

A relatively good lithostratigraphic correlation exists between Feibel's (1983) stratigraphic columns on which Lepre et al. (2007) based their model of deposition and the stratigraphic sections measured in this study. This correlation was made possible by calculating a linear sedimentation rate between the KBS Tuff and the top of the Olduvai Normal Subchron and another linear sedimentation rate between the top of the Olduvai Normal Subchron (1.778 Ma) and the Black Pumice Tuff (1.527) 1 m below T10 (L. Ileret Tuff). These sedimentation rates were calculated using the generalized stratigraphic column presented by Feibel (1983). Once rates were determined they were used to place ages on each of the major stratigraphic units. These ages were then

Table 8. Schematic representation of the tuff correlations between the Koobi Fora, Shungura, Nachukui and Konso Formations (Francis Brown, personal communication, 2010).

Koobi Fora	Shungura	Nachukui	Konso
KFTC (BPT at base; 1.53Ma)[#]	Tuff J-7	BPT	
Morutot Tuff (1.607 Ma)*	Tuff J-4	Morutot Tuff	
Asa Tuff	ETH08-240	K07-520?	
			Kayle Tuff 2 (1.735)*
Orange Tuff	Tuff J	Orange Tuff	Kayle Tuff 1
Steel Grey Tuff			
Malbe Tuff (1.843 Ma)*	Tuff H4	Malbe Tuff	
KBS Tuff (1.867 Ma)*	Tuff H2	KBS Tuff	

[#] Brown et al, 2006
* McDougal and Brown, 2006

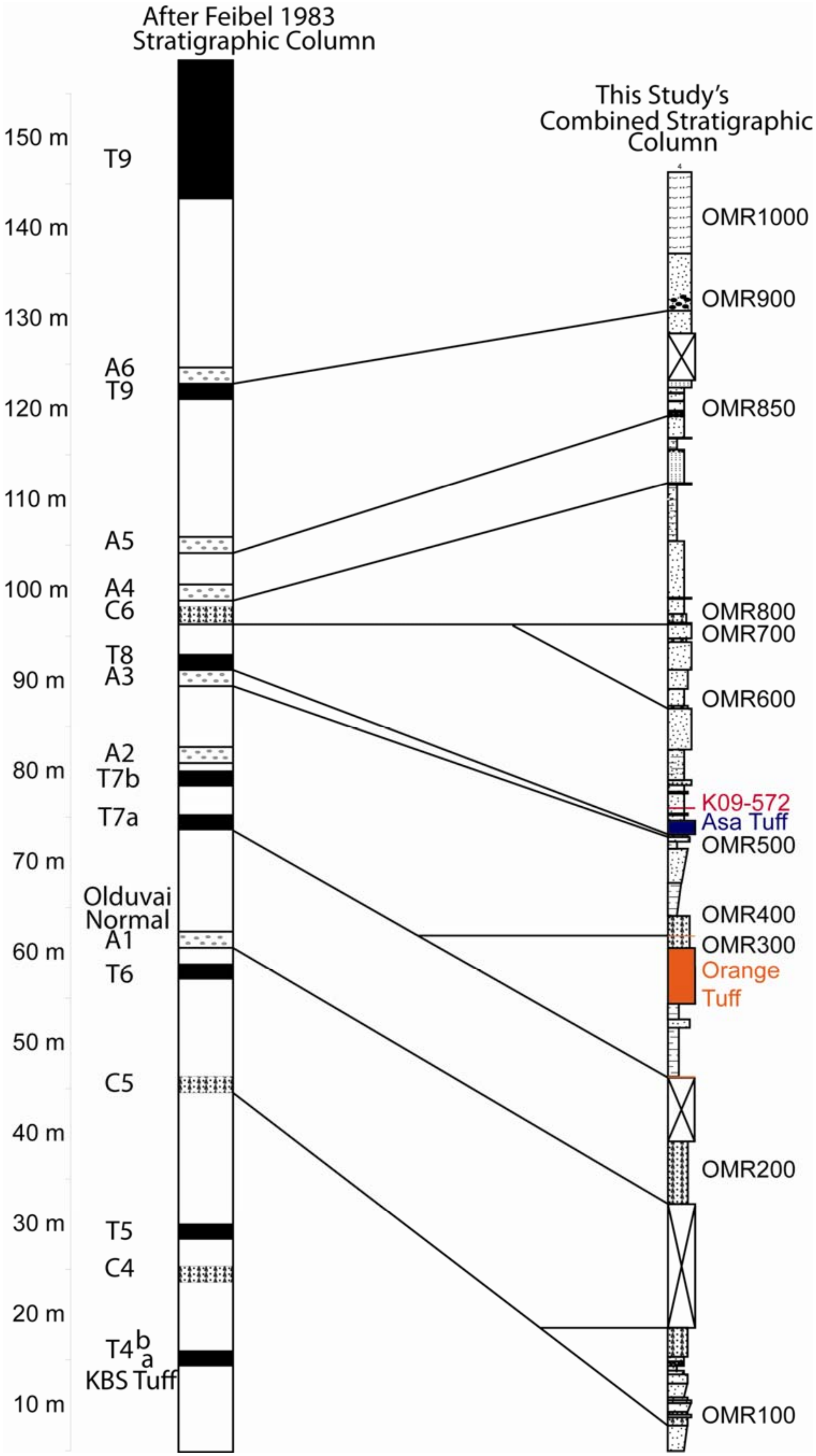
compared to ages of Northern Hemisphere Insolation maxima calculated by Lourens et al. (1998) and related to sapropels in the Mediterranean by the work of Kroon et al. (1998) and to dust peaks described in cores from the Gulf of Aden by de Menocal (2004). Once all of these ages were taken into account along with the age of each of the dated tuffs and the top of the Olduvai Normal Subchron it became possible correlate the stratigraphic column of Feibel (1983) to the stratigraphic column for Areas 106, 107, and 109 established in this study (Table 9 and Figure 16). In making this correlation it was important to keep in mind that bioclastic beds can change laterally from mollusc-packed sandstones to algal beds. This lateral change is caused by the specialized niches each type of organism occupies and their deposition within a single bed at a given time, thus allowing the correlation of algal beds to mollusc beds.

Lepre et al. (2007) relate fluctuations in the level of Lake Turkana to Milankovitch cycles which are known from studies of sapropels in the Mediterranean Sea(Rossignol and Strick, 1985; Emeis and Sakamoto, 1998; Kroon et al., 1998) to drive the intensity of monsoonal rains over the Ethiopian highlands. These highlands are the headwaters of the Omo River which feeds Lake Turkana. Thus any change in precipitation over them affects the level of Lake Turkana. Lepre et al. (2007) propose that ABCs are the result of low lake levels because ABCs form in near shore environments. After comparing the composite stratigraphic section compiled during this study to Milankovitch cycles, it becomes clear that ABCs are not simply the result of Milankovitch cycles. This conclusion was drawn because the Orange Tuff dates between 1.735 and 1.61Ma and the top of the Olduvai Normal Subchron dates to 1.778 Ma,

Table 9. Summary of ages that may apply to major lithologic markers in Areas 106, 107 and 109 with correlation to their lithologic equivalents in Areas 102 and 103.

						Kroon	*Lourens*	*de Menocal*	**Suggested Ages**
This Study	Lepre 2007 and 2010	Known	Calc Age	Calc Age	Lepre et al.	Dry	Dry	Dust	
	T10 (B. Pumice)	1.527							**1.527**
OMR900	A6		1.583		1.552	1.574		1.573	**1.57**
	T9 (Chabazite)		1.589			1.594	1.598	1.593	**1.59**
OMR850	A5		1.614		1.624	1.613	1.615		**1.62**
	A4		1.660		1.644	1.632	1.635	1.638	**1.64**
OMR800	C6		1.670		1.664	1.668	1.655	1.666	**1.67**
	T8		1.679						**1.68**
OMR500	A3		1.685		1.696		1.670		**1.69**
	A2		1.713		1.748		1.714	1.705	**1.71**
	T7b		1.722				1.725	1.725	**1.73**
Orange Tuff	T7a		1.738			1.746	1.75	1.747	**1.75**
OMR200	A1 (Olduvai N.)	1.778			1.778	1.782	1.775	1.787	**1.778**
	T6			1.786					**1.79**
OMR100	C5			1.811	1.811	1.818	1.798	1.816	**1.81**
	T5			1.840					**1.83**
	C4			1.850	1.851	1.84	1.840	1.841	**1.84**
	T4b (Malbe)	1.843		1.843					**1.843**
	KBS (T4a)	1.869				1.861	1.860	1.866	**1.869**

Figure 16. Stratigraphic correlation between the generalized composite column for Areas 101, 102 and 103 (Feibel, 1983) and the composite stratigraphic column established in this study. Branched tie lines represent correlations from a single bed in Feibel's study area to multiple beds found in the study area.


After Feibel 1983
Stratigraphic Column
This Study's
Combined Stratigraphic
Column
150 m
140 m
130 m
120 m
110 m
100 m
90 m
80 m
70 m
60 m
50 m
40 m
30 m
20 m
10 m
T9
A6
T9
A5
A4
C6
T8
A3
A2
T7b
T7a
Olduvai
Normal
A1
T6
C5
T5
C4
T4 b a
KBS Tuff
OMR1000
OMR900
OMR850
OMR800
OMR700
OMR600
K09-572
Asa Tuff
OMR500
OMR400
OMR300
Orange
Tuff
OMR200
OMR100

forcing the Orange Tuff to correlate with Feibel's T7a, T7b or T8, if it correlates with any of these units at all. Of these three choices T7a appears to be the most likely because this correlation allows the Asa Tuff to be correlated to T7b. Assuming the best case scenario where the Orange Tuff correlates with T7a according to Feibel's section, there should be two algal beds above it, A2 and A3. This, however, is not the finding of this study. In fact there are no algal beds between the Orange Tuff and C6 but there are 6 ABCs. This means that the number of ABCs present in a local is location dependent and that the relation to Milankovitch cycles is complex, rather than simple.

It is worth considering the probable meaning of algal biolithites and mollusc-packed sandstones a little more thoroughly. As Lepre et al. (2007) note:

> The depositional environments for the stromatolites have been interpreted as shallow littoral areas, and nearshore photic zone sites with evaporative and hypersaline conditions (Johnson, 1974; Abell et al., 1982; Casanova, 1986). Mollusks include the gastropods *Bellamya, Cleopatra*, and *Melanoides*, and the bivalve *Mutela*, which together indicate relatively fresh waters as compared with the stromatolites (Williamson, 1982). The sandy beds intercalated with and adjacent to the ABC units resemble deposits from the beachface/shoreface settings of other well-studied lake margins (e.g., Renaut and Owen, 1991; Blair, 1999). All of these data suggest nearshore depositional settings, with extensive and shallow shorelines of little relief, and beach areas (e.g., Feibel, 1983, 1988; Tindall, 1986).

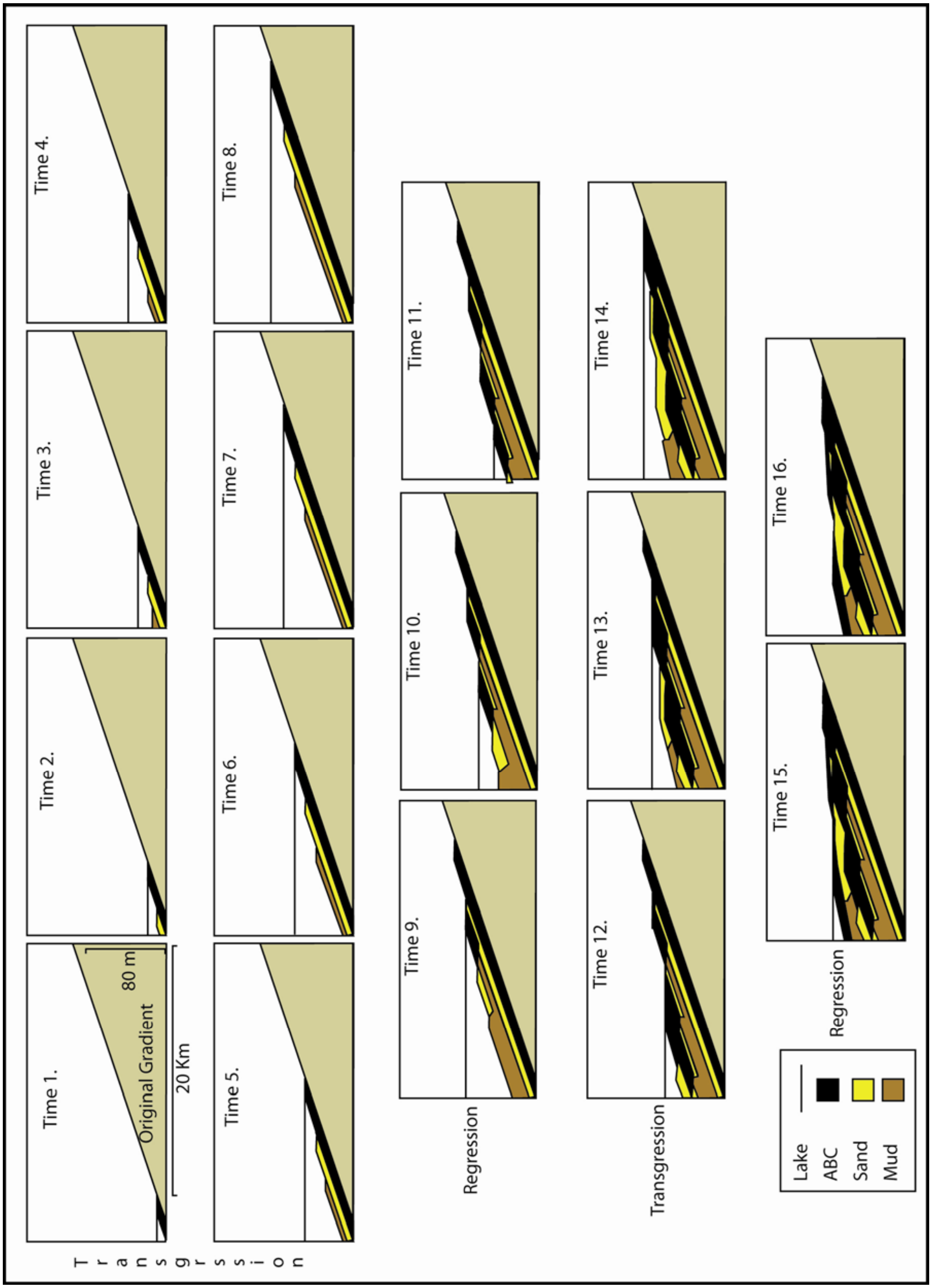
Topographic gradients from the lakeshore toward the basin margin today are low, but nonetheless quite significant. Along Il Eriet, a large ephemeral stream, north of the study area, one finds an elevation of 410 m 12.5 km away from the lake, giving a gradient of 0.004; for Il Alia, which forms the southern boundary of the study area, one finds a gradient of ~0.002 over 15 km; along Il Lokochot, still farther south, the gradient is ~0.0075. Assuming that gradients during the time of deposition of the Koobi Fora Formation are similar to those of today, and noting that mollusc-packed sandstones of the

KBS Member extend at least 20 km east of the modern lakeshore, it is a simple matter to compute that the lakeshore at its easternmost extent must have been on the order of 40 to 80 m higher than the present lake shore. From studies of the Galana Boi Formation (Owen and Renaut, 1986) and the Kibish Formation it is known that in time spans of <10 ka (0.01 Ma), the level of Lake Turkana can vary by similar amounts—approximately 85 m for the last highstand (Brown and Fuller, 2008). Suppose that one could trace a single mollusc-packed sandstone from Koobi Fora (in the west) to the region near Shin (in the east), a distance of ~20 km. At each location along the transect, this sandstone would represent marginal lacustrine conditions, but the climatic interpretation of its occurrence would be different. In the west, it would represent a time of low lake level (hence a dry episode), whereas in the east, it would represent a time of high lake level (hence a time when monsoonal rains had intensified), yet the lithology would be the same. In this way, we see that the meaning of a mollusc-packed sandstone changes depending on location.

Lepre et al. (2007) note that some of the best developed mollusc-packed sandstones are exposed over ~250 km^2, and given the ~12.5 km width of the western Koobi Fora Ridge, this necessitates that they must extend approximately 20 km east of the present shoreline, which is their westernmost known extent. Therefore, even a continuous mollusc-packed sandstone does not represent an isochronous layer; instead its age, as well as its climatic significance is location dependent (Figure 17). Two considerations compound this problem further, one is the matter of tectonic movements, for even movements on the order of a few meters will be significant to the geographic location of the shoreline; the second is that we do not know the actual western limit of any mollusc-packed sandstone—only that they extend as far west as the end of outcrops along the lakeshore. It is possible that they actually extend for several kilometers farther westward, in which case, the exposures along western Koobi Fora Ridge would refer neither to a particularly wet time, nor to a particularly dry time, but rather to conditions somewhere in between. Gathogo (2003) has shown that faulting was active during the time of deposition of at least part of the Okote Member at Ileret, so there is no reason to assume that similar movements did not affect the western end of Koobi Fora Ridge.

It should be noted, however, that the deposition of an ABC near the Turkana Basin margin is representative of a wet period and an ABCs presence near the basin center is indicative of a dry period. This is known because as the lake spreads or shrinks laterally due to water flux the nearshore facies must move with it. One might argue that the ABCs from this study and that of Lepre et al. (2007) are in fact near the basin center and thus must be indicative of dry periods. This cannot be assumed due to tectonic activity observed by Gathogo (2003). This may mean that the modern topography does not accurately represent the topography on which the strata were deposited, limiting the assumptions that can be made as to whether a particular bed was deposited during a wet, dry or intermediate period of time.

Figure 17. Time sequence of how mollusc-packed sandstone deposition in Lake Turkana might develop in an idealized cross section. Note extreme vertical exaggeration. True gradients range between 0.002 and 0.0075.


Transgression
Time 1.
Original Gradient
80 m
20 Km
Time 2.
Time 3.
Time 4.
Time 5.
Time 6.
Time 7.
Time 8.
Regression
Time 9.
Time 10.
Time 11.
Transgression
Time 12.
Time 13.
Time 14.
Regression
Time 15.
Time 16.
Lake
ABC
Sand
Mud

7. CONCLUSIONS

The Koobi Fora Formation has been the focus of many studies, however little detailed work had been done in Areas 106, 107 and 109 (~11 km southeast of Koobi Fora) prior to this study. In this study, exposures of the KBS and the upper Burgi Members of the Koobi Fora Formation were found. The upper Burgi Member is only exposed in very low lying outcrops in the southern portion of the study area (Area 109) so no attempt was made to establish a stratigraphic section for this unit in this area. All other strata in the study area belong to the KBS Member and total ~145 m of section.

The KBS Member (~1.9–1.6 Ma) was deposited in and along the margins of a large lake, known as ancient Lake Turkana, mainly in nearshore lacustrine settings as lake level fluctuated. During these fluctuations mollusc-packed sandstones were deposited in the nearshore environment of ancient Lake Turkana. Mollusc-packed sandstones are poorly- to well-cemented, and form easily mapped pavements that allow both stratigraphic and structural control throughout the study area.

Four tuffs known from previous studies have been identified within the KBS Member in the study area: the KBS Tuff, the Brown Tuff, the Orange Tuff and the Asa Tuff. In addition to the named tuffs, another tuff, K09-572 lies about 5 m above the Asa Tuff. The KBS Tuff is well dated at 1.869 ± 0.021 Ma, but direct ages have not been measured on any of the other tuffs described. Although this is the case, Brown (unpublished) has correlated the Orange Tuff with Tuff J of the Shungura Formation, and also with the Kayle Tuff-1 at Konso in Ethiopia. The Kayle Tuff-1 lies 2.5 m below the Kayle Tuff-2 which has been dated at 1.735 ± 0.03 Ma. In the Nachukui Formation, west of Lake Turkana, the Asa Tuff lies below the Morutot Tuff, hence its age is between 1.735 and 1.61 Ma. Tuff J is known to lie above the top of the Olduvai Event, for which the current age estimate is 1.778 Ma (Gradstein, Ogg and Smith, 2004).

Dating of sapropels in the Mediterranean Sea and dust peaks in the Gulf of Aden by other workers was done in an effort to correlate them with insolation maxima in Milankovitch cycles. Milankovitch cycles are important in the context of this study because they are thought to drive the intensity of monsoonal rains over the Ethiopian highlands whose southern divide drains into Lake Turkana via the Omo River. Studies by Lepre et al (2007) have applied ages of the insolation minima between sapropels to the mollusc-packed sandstones and algal beds in Areas 102 and 103 to the north of the study area, based on the idea that these beds only form during climatically dry periods. The available chronological control in Areas 102 and 103 provided a reasonable fit to the number and approximate age of these units. Additional age control provided by the Orange Tuff suggests that at least in Areas 106, 107, and 109 the number of mollusc-packed sandstones and algal beds present within a local section is location dependent, and cannot obviously be correlated with Milankovitch cycles. Most importantly these beds need to be thought of as diachronous not isochronous. In order to assume that a mollusc-packed sandstone or algal bed was formed during a dry period it must be near the basin center, the opposite can also be assumed, mollusc-packed sandstones formed near the basin margin can be assumed to have formed during wet periods of time.

APPENDIX

Sample locations:

Sample #	Latitude	Longitude	Tuff Name
OMR08-1	3.8071	36.2802	KBS
OMR08-2	3.8085	36.2814	KBS
OMR08-3	3.8087	36.2843	Brown
OMR08-4	3.8151	36.2850	KBS
OMR08-5	3.8189	36.2608	Orange Tuff
OMR08-6	3.8189	36.2616	Orange Tuff
OMR08-7	3.8189	36.2616	Orange Tuff
OMR08-9	3.8165	36.2594	Orange Tuff
OMR08-11	3.8364	36.2560	Orange Tuff
OMR08-12	3.8383	36.2568	Asa
OMR08-13	3.8394	36.2630	Asa
OMR08-14	3.8423	36.2697	Asa
OMR08-15	3.8423	36.2697	Asa
OMR08-16	3.8365	36.2609	Asa
OMR08-18	3.8805	36.2583	Asa
OMR08-21	3.8513	36.2443	Asa
OMR08-22	3.8855	36.2563	Asa
OMR08-23	3.8896	36.2564	Asa
OMR08-24	3.9003	36.2508	Asa
K09-572	3.8652	36.3037	unnamed

REFERENCES

Arambourg, C., 1943, Mission scientifique de l-Omo, 1932–1933. Tome I: Paris, France, Museum National d`Histoire Naturelle, p. 51–55.

Baker, B.H., Mohr, P.A., and Williams, L.A.J., 1972, Geology of the Eastern Rift System of Africa: Geological Society of America Special Paper 136, p. 67. [Where is this cited in the text?]

Bethany House, Lodwar temperature and climate, http://www.lodwar.org/climate-time.htm, (accessed February 5, 2010.)

Bowen, B. E., 1974, The geology of the Upper Cenozoic sediments in the East Rudolf embayment of the Lake Rudolf basin, Kenya [Dissertation thesis]: Ames, Iowa State University. 164 p.

Bowen, B.E., and Vondra, C.F., 1973, Stratigraphical Relationships of the Plio-Pleistocene Deposits, East Rudolf, Kenya: Nature, v. 242, p. 391–393.

Bowen, B.E., Vondra, C.F., Johnson, G.D., and Behrensmeyer, A.K., 1972, The Hominid-Bearing Pleistocene Sequences of the East Rudolf Basin, Kenya: G.S.A. Abstract with Programs v. 4, p. 310.

Brown, F.H., 1994, Development of Pliocene and Pleistocene chronology of the Turkana Basin, East Africa, and its relation to other sites, *in* Ciochon, R., and Corruccini, R., eds., Integrative Paths to the Past: Englewood Cliffs, Prentice Hall, p. 285–312.

Brown, F.H., and Cerling, T.E., 1982, Stratigraphical significance of the Tulu Bor Tuff of the Koobi Fora Formation: Nature, v. 299, p. 212–215.

Brown, F.H., and Feibel, C.S., 1985, Stratigraphic notes on the Okote Tuff Complex at Koobi Fora: Nature, v. 316, p. 794–797.

Brown, F.H., and Feibel, C.S., 1986, Revision of lithostratigraphic nomenclature in the Koobi Fora region, Kenya: Journal of the Geological Society, v. 143, p. 297–310.

Brown, F.H., and Feibel, C.S., 1991, Stratigraphy, depositional environments and paleogeography of the Koobi Fora Formation, *in* Harris, J.M., ed., Koobi Fora Research Project, Volume 3: Stratigraphy, artiodactyls and paleoenvironments: Oxford, Clarendon Press, p. 1–30.

Brown, F.H., Howell, F.C., and Eck, G.G., 1978, Observations on problems of correlation of the late Cenozoic hominid-bearing formations in the north Lake Turkana basin, *in* Bishop, W.W., ed., Geological background to fossil man: Edinburgh, Scottish Academic Press, p. 473–498.

Brown, F.H., and Feibel, C.S., 1997, Lithostratigraphic terminology of Plio-Pleistocene sediments of the Koobi Fora Region, Koobi Fora Research Project, Volume 5: Oxford, Clarendon Press, p. 60–64.

Brown, F.H., Haileab, B., and McDougall, I., 2006, Sequence of tuffs between the KBS Tuff and the Chari Tuff in the Turkana Basin, Kenya and Ethiopia: Journal of the Geological Society, v. 163, p. 185–204.

Brown, F.H., and Fuller, C.R., 2008, Stratigraphy and tephra of the Kibish Formation, southwestern Ethiopia: Journal of Human Evolution, v. 55, p.366–403.

Burggraf, D.R.J., 1976, Stratigraphy of the Upper Member, Koobi Fora Formation, southern Karari Escarpment,East Turkana Basin, Kenya, Master's Thesis, Iowa State University, Ames, Iowa, 116 p.

Butzer, K.W., Isaac, G.L., Richardson, J.L., and Washbourn-Kamau, C., 1972, Radiocarbon dating of East African lake levels: Science, v. 175, p. 1069–1076.

Casanova, J., 1986, East African Rift stromatolites, *in* Frostick, L.E., Renaut, R.W., Reid, I., and Tiercelin, J.J., eds., Sedimentation in the African rifts. Blackwell: Oxford, p. 201–210.

Cerling, T.E., 1977, Paleochemistry of Plio-Pleistocene Lake Turkana and diagenesis of its sediments [Dissertation thesis]: Berkeley, University of California.

Cerling, T.E., and Brown, F.H., 1982, Tuffaceous marker horizons in the Koobi Fora region and the lower Omo valley: Nature, v. 299, p. 216–221.

Cerling, T.E., Bowman, J.R., and O'Neil, J.R., 1988, An isotopic study of a fluvial-lacustrine sequence: the Plio-Pleistocene Koobi Fora sequence, East Africa: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 63, p. 335–356.

Cerling, T.E., Brown, F.H., Cerling, B.W., Curtis, G.H., and Drake, R.E., 1979, Preliminary correlations between the Koobi Fora and Shungura Formations, East Africa: Nature, v. 279, p. 118–121.

Compton, R. R., 1962, Manual of Field Geology: New York, Wiley and Sons, 378 p.

Cooke, H.B.S., 1972, Pleistocene Chronology: Long or Short?: Maritime Sediments, v. 8, p. 1–12.

Cooke, H.B.S., and Maglio, V.J., 1972, Plio-Pleistocene stratigrapy in East Africa in relation to proboscidean and suid evolution, *in* Bishop, W.W., and Miller, J.A., eds., Calibration of Hominoid Evolution: Edinburgh, Scotland, Scottish Academic Press, p. 303–329.

Davidson, A., (ed.) 1973, Omo River Project Preliminary Report, Addis, Ethiopian Government Ministry of Mines, 21 p.

De Menocal, P.B., 2004, African climate change and faunal evolution during the Pliocene-Pleistocene: Earth and Planetary Science Letters, v. 220, p. 3–24.

Ebinger, C. J. and Yemane, T., 2000, Rift deflection, migration, and propagation: Linkage of the Ethiopian and Eastern Rifts, Africa: GSA Bulletin, v. 112, p. 163–176.

Emeis, K.C., and Sakamoto, T., 1998, The sapropel theme of Leg 160, *in* Robertson, A.H.F., Emeis, K.C., Richter, C., and Camerlenghi, A., eds., Proceedings of the Ocean Drilling Program, Scientific Results, v. 160, p. 29–36.

Feibel, C.S., 1981, Preliminary Report on the Stratigraphy of the Koobi Fora Formation along the Western Koobi Fora Ridge, East Turkana, Kenya, p. 1–15.

Feibel, C.S., 1983, Stratigraphy and paleoenvironments of the Koobi Fora Formation along the western Koobi Fora Ridge, East Turkana, Kenya [Unpublished M. S. Thesis]: Ames, Iowa State University.

Feibel, C.S., 1988, Paleoenvironments of Koobi Fora Formation [Dissertation thesis]: Salt Lake City, University of Utah.

Feibel, C.S., and Brown, F.H., 1986, Depositional history of the Koobi Fora Formation, northern Kenya, Second Conference on the Geology of Kenya.

Feibel, C.S., Brown, F.H., and McDougall, I., 1989, Stratigraphic context of fossil hominids from the Omo Group deposits, northern Turkana Basin, Kenya and Ethiopia: American Journal of Physical Anthropology, v. 78, p. 595–622.

Feibel, C.S., Harris, J.M., and Brown, F.H., 1991, Neogene paleoenvironments of the Turkana Basin, *in* Harris, J.M., ed., Stratigraphy, artiodactyls and paleoenvironments, Volume 3: Koobi Fora Research Project:: Oxford, Clarendon Press, p. 321-370.

Findlater, I.C., 1976, Stratigraphic analysis and palaeoenvironmental interpretation of a Plio/Pleistocene sedimentary basin east of Lake Turkana [Dissertation thesis]: London, University of London.

Findlater, I.C., 1978a, Isochronous surfaces within the Plio-Pleistocene sediments east of Lake Turkana, *in* Bishop, W.W., ed., Geological background to fossil man: Edinburgh, Scottish Academic Press, p. 415–420.

Findlater, I.C., 1978b, Stratigraphy, *in* Leakey, M.D., and Leakey, R.E.F., eds., The fossil hominids and an introduction to their context, Volume 1: Koobi Fora Research Project: Oxford, Clarendon Press, p. 14–31.

Fitch, F.J., and Miller, J.A., 1976, Conventional potassium-argon and argon-40/argon-39 dating of volcanic rocks from East Rudolf, *in* Coppens, Y., Howell, F.C., Isaac, G.L., and Leakey, R.E.F., eds., Earliest man and environments in the Lake Rudolf Basin; stratigraphy, paleoecology, and evolution: Chicago, University of Chicago Press, p. 123–147.

Gathogo, P.N., 2003, Stratigraphy and paleoenvironments of the Koobi Fora Formation of the Ileret Area, Northern Kenya [Unpublished M. S. Thesis]: Salt Lake City, Univeristy of Utah.

Gathogo, P. N., Brown, F. H., and McDougall, I., 2008, Stratigraphy of the Koobi Fora Formation (Pliocene and Pleistocene) in the Loiyangalani region of northern Kenya: Journal of African Earth Sciences, v. 51, p. 277–297.

Gradstein F.M., et al., 2004, A new Geologic Time Scale, with special reference to Precambrian and Neogene: Episodes, 2004, p. 83–100.

Hahn, G., Raynolds, R., Wood, R., and Johnson, G., 1973a, Summary of mapping - Area 102, Koobi Fora Formation, 1973.

Hahn, G., Wood, R., and Raynolds, R., 1973b, Area 102 report. [Unpublished]

Harris, J.M., 1991, Stratigraphy, artiodactyls and paleoenvironments: Koobi Fora Research Project, Oxford, Clarendon Press, v. 3, p. 321–346.

Hendrie, D.B., Kusznir, N.J., Morley, C.K., and Ebinger, C.J., 1994, Cenozoic extension in northern Kenya: a quantitative model of rift basin development in the Turkana area: Techonophysics, v. 236, p. 409–438.

Isaac, G.L., 1973, Early Artefact Assemblages From the Koobi Fora Formation, LakRudolf, Kenya, Paleoecology and Evolution in the Lake Rudolf Basin, Wenner-Gren Foundation for Anthropological Research, p. 1–11.

Johnson, G.D., 1973a, Summary of mapping - Area 103, Koobi Fora Formation, 1972, Koobi Fora Archives: Nairobi, National Museums of Kenya, p. 15.

Johnson, G.D., 1973b, Rationle of paleoenvironmental interpretation of East Rudolf sediments: the importance of alluvial pedogenesis, Koobi Fora Archives: Nairobi, National Museums of Kenya, p. 13.

Johnson, G.D., 1973c, Late Cenozoic environments of the Koobi Fora Formation: the Upper Member along the western Koobi Fora Ridge, Koobi Fora Archives: Nairobi, National Museums of Kenya, p. 28.

Johnson, G.D., 1974, Cainozoic lacustrine stromatolites from hominid-bearing sediments east of Lake Rudolf, Kenya: Nature, v. 247, p. 520–523.

Johnson, G.D., and Raynolds, R.G.H., 1976, Late Cenozoic environments of the Koobi Fora Formation: the Upper Member along the western Koobi Fora Ridge, *in* Coppens, Y., Howell, F.C., Isaac, G.L., and Leakey, R.E.F., eds., Earliest man and environments in the Lake Rudolf basin: Chicago, University of Chicago Press, p. 115–122.

Katoh, S., Nagaoka, S., WoldeGabriel, G., Renne, P.R., Snow, G.M., Beyene, Y., and Suwa, G., 2000, Chronostratigraphy and correlation of the Plio-Pleistocene tephra layers of the Konso Formation, southern Main Ethiopian Rift, Ethiopia: Quaternary Science Reviews, v. 19, p. 1305–1317.

Keller, E., 2002, Active Tectonics, Upper Saddle River, Prentice-Hall, Inc

Kroon, D., Alexander, I., Little, M., Jourens, L.J., Matthewson, A., Robertson, A.H.F., and Sakamoto, T., 1998, Oxygen Isotope and sapropel stratigraphy in the eastern Mediterranean during the last 3.2 Million years, *in* Robertson, A.H.F., Emeis, K.C., Richter, C., and Camerlenghi, A., eds., Proceedings of the Ocean Drilling Program, Scientific Results, Volume 160, p. 181–189.

Lepre et al., 2007, Plio-Pleistocene facies environments from the KBS Member, Koobi Fora Formation: implications for climate controls on the development of lake-margin hominin habitats in the northeast Turkana Basin (northwest Kenya): Jounal of Human Evolution, v. 53, p. 503–514.

Lepre et al., 2010, New magnetostratigraphy for the Olduvai Subchron in the Koobi Fora Formation, northwest Kenya, with implications for early Homo: Earth and Planetary Science Letters, in press.

Lourens, L.J., Hilgen, F.J., and Raffi, I., 1998, Base of large *Gephyrocapsa* and astronomical calibraton of early Pleistocene Sapropels in Site 967 and Hole 969D: Solving the chronology of the Vrica Section (Calabria, Italy), *in* Robertson, A.H.F., Emeis, K.C., Richter, C., and Camerlenghi, A., eds., In Proceedings of the Ocean Drilling Program: Scientific Results, v.160, p. 191–197.

McDougall, I., Davies, T., Maier, R., and Rudowski, R., 1985, Age of the Okote Tuff Complex at Koobi Fora, Kenya: Nature, v. 29, p. 792–794.

McDougall, I., Maier, R., Sutherland-Hawkes, P., and Gleadow, A.J.W., 1980, K-Ar age estimate for the KBS Tuff, East Turkana, Kenya: Nature, v. 284, p. 230–234.

McDougall, I., and Brown, F.H., 2006, Precise $^{40}Ar/^{39}Ar$ geochronology for the upper Koobi Fora Formation, Turkana Basin, northern Kenya: *J. Geol. Soc. Lond.*, v. 163, p. 205–220.

McDougall, I., and Brown, F. H., 2008, Geochronology of the pre-KBS Tuff sequence, Omo Group, Turkana Basin: Journal of the Geological Society, v. 165, p. 549–562.

Nash, W.P., 1992, Analysis of oxygen with the electron microprobe: Applications to hydrated glass and minerals: American Mineralogist, v. 77, p. 453–457.

Owen, R.B., and Renaut, R.W., 1986, Sedimentology, stratigraphy and paleoenvironments of the Holocene Galana Boi Formation, NE Lake Turkana, Kenya, *in* Frostick, L.E., Renaut, R.W., Reid, I., and Tiercelin, J.J., eds., Sedimentation in the African rifts: Oxford, Blackwell, v.25, p. 311–322.

Pouchou, J.L., and Pichoir, F., 1991, Quantitative analysis of homogeneous or stratified microvolumes applying the model "PAP", *in* Heinrich, K.F.J., and Newbury, D.E., eds., Electron probe quantitation: New York, Plenum Press, p. 31–75.

Raynolds, R.G.H., 1972, Summary of mapping - Area 103, Galana Boi Beds, 1972: Hanover, Dartmouth.

Renaut, R.W. and Owen, R.B., 1991, Shore-zone sedimentation and facies in a closed rift lake: the Holocene beach deposits of Lake Bogoria, Kenya. *in* P. Anadon, L. Cabrera and K. Kelts, Editors, Lacustrine Facies Analysis: International Association of Sedimentologists, Special Publlication. p. 175–195.

Rosendahl, B. R., 1987, Architecture of continental rifts with special reference to East Africa: Annual Review of Earth and Planetary Sciences, v. 15, 445–503.

Rossignol and Strick, M., 1985, Mediterranean Quaternary sapropels, an immediate response of the African monsoon to variations of insolation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 49, p. 237–263.

Tindall, K.W., 1983, Stratigraphy of the eastern Koobi Fora Ridge, East Turkana Basin, Kenya. Abstracts with Programs Geological Society of America, v. 15, p. 266.

Tindall, K.W., 1985, Stratigraphy and sedimentology of the Koobi Fora Formation, eastern Koobi Fora Ridge, East Turkana, Kenya: Ames, Iowa State University.Vondra, C.F., and Bowen, B.E., 1976, Plio-Pleistocene deposits and environments, East Rudolf,Kenya, *in* Coppens, Y., Howell, F.C., Isaac, G.L., and Leakey, R.E.F., eds., Earliest man and environments in the Lake Rudolf basin: Chicago, University of Chicago Press, p. 79–93.

Vondra, C.F., and Bowen, B.E., 1978, Stratigraphy, sedimentary facies and paleoenvironments, East Lake Turkana, Kenya, *in* Bishop, W.W., ed., Geological background to fossil man: Edinburgh, Scottish Academic Press, p. 395–414.

Vondra, C.F., Johnson, G.D., Bowen, B.E., and Behrensmeyer, A.K., 1971, Preliminary stratigraphical studies of the East Rudolf basin, Kenya: Nature, v. 231, p. 245–248.

Walsh, J., and Dodson, R. G., 1969, Geology of northern Turkana: Report 82, Kenya, Geologic Survey, Nairobi, Kenya, 42 p.

Watkins, R.T., 1986, Volcano-tectonic control on sedimentation in the Koobi Fora sedimentary basin, Lake Turkana, *in* Frostick, L.E., Renaut, R.W., Reid, I., and Tiercelin, J.J., eds., Sedimentation in the African rifts, Geological Society Special Publication, Oxford, Blackwell, v. 25, p. 85–95.

White, H. J. 1976, Stratigraphy of the Lower Member, Koobi Fora Formation, southern Karari Escarpment, East Turkana Basin, Kenya. [Unpublished M. S. Thesis]: Ames, Iowa State University. 134 p.

Wilkinson, A. F., 1988. Geology of the Allia Bay area: Report of the Mines and Geology Department, Kenya, v. 109, p. 54.

Williams, L.A.J., 1969, Volcanic Associations in the Gregory Rift Valley, East Africa: Nature, v. 224, p. 61-64.

Williams, L.A.J., 1978, The Volcanological Development of the Kenya Rift, *in* Neumann, E.R., and Ramberg, I.B., eds., Petrology and Geochemistry of Continental rifts: Dordrecht, Dr. Reidel Publishing company, p. 101-121.

Williamson, P.G., 1982, Molluscan biostratigraphy of the Koobi Fora hominid-bearing deposits: Nature, v. 295, p. 140–142.